MASS TRANSFER AT ROTATING CYLINDERS

by

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ABSTRACT

Rates of mass transfer at circular cylinders rotating about their axes in the center of stationary cylinders were studied by means of solid dissolution and electrolytic redox reactions. Benzoic and Cinnamic acids cast into cylinders were dissolved into water and water-glycerol solutions. Alkaline potassium ferri- and ferrocyanide solutions in the concentration range 0.01 to 0.20 molar were used to study mass transfer rates (through measurements of limiting current densities) and the polarization associated with the cathodic reduction of $Fe(CN)_6^{-3}$ and anodic oxidation of $Fe(CN)_6^{-4}$ on nickel electrodes.

In a study involving a large variation of cylinder diameters and their ratios the magnitude of the gap was found not to affect the rates of mass transfer under turbulent flow conditions. The study covered a Schmidt number range of 835 to 11,490 and a Reynolds number range of 112 to 241,000.

A general correlation of the mass transfer data was obtained in which the j' (defined as $k/V\,Sc^{0.644}$, k = mass transfer coefficient, V = peripheral velocity, Sc = Schmidt number) is expressed as a function of the Reynolds number R_d, based on the rotor diameter. Close agreement of the j_D parameter values with the friction coefficients f/2, determined by Theodorsen and Regier, was found.

I. INTRODUCTION

The present investigation of forced convection mass transfer was carried out on rotating cylinders because of the particular interest that such a study has for the interpretation of phenomena associated with electrolytic reactions (9).

The effect of the speed of rotation upon the rate of mass transfer was first studied by Brunner (3). He expressed his findings in the form of the diffusion layer thickness δ

$$\delta = \frac{0.05}{R^{2/3}} \text{ cm} \qquad (1)$$

where R = rotation speed, rpm and δ is defined (28) by Equation (2)

$$N = \frac{D \cdot \Delta c}{\delta} \qquad (2)$$

where N = rate of mass transfer, mols/cm^2-sec

Δc = concentration difference between bulk solution and electrode surface, moles/cm^3

However, Brunner, who covered speeds in the vicinity of 150 rpm, considered neither the effect of rotor diameter nor the physical properties of the electrolyte. Furthermore the geometries of the cells used (3)(20) do not afford any clear definition of the hydrodynamic conditions and, therefore, only qualitative deductions can be made for different experiments.

The methods of hydrodynamics were applied for the first time by Eucken (10) to predict the effect of forced convection upon the rate of mass transfer at an electrode. In his experiments he rotated an external vessel containing the solution so that a laminar flow past a stationary flat plate electrode was produced.

Recently Roald and Beck (23) have used such rotating cylinders in a study of rates of dissolution of magnesium and its alloys in

hydrochloric acid solutions. They found that the rate of dissolution increasedwith the 0.71 power of the speed of rotation in the region of low acid concentrations. At higher acid concentrations (1.4 molar and higher) the reaction rates become entirely independent of rotational speeds, as the stirring effect produced by the hydrogen bubbles evolving at the metal interface becomes predominant. This stirring effect, however, cannot be ignored even at low acid concentrations because of turbulence caused by the hydrogen bubbles moving in the boundary layer adjacent to the dissolving magnesium rod. For this reason the work of Roald and Beck in addition to being limited in scope, represents a rather special case of forced convection mass transfer at rotating cylinders.

The present work involving studies of rates of solid dissolution and of electrolytic redox reactions was undertaken with the aim to establish a general mass transfer correlation between the physical properties of a system, geometrical and hydrodynamic conditions and the rates at which a solute is transferred to or from a rotating cylinder.

II. EXPERIMENTAL

1. Dissolution Studies of Solids Cast into Rotating Cylinders

(a) Apparatus

A concentric cylindrical cell, 6.16 inches high, built from acrylic plastic (lucite) was constructed in such a manner that the grooved end plates could hold, according to need, one of three cylindrical tubes of internal diameters 2.48, 4.00 and 5.47 inches (see Figures 1 and 2). A 1/2" diameter stainless steel driving shaft passed through a teflon packing gland in the center of the top plate and was equipped with a 1/4" std. thread which allowed cylinders of

various diameters to be screwed on to it prior to the assembling of the cell. The rotated cylinder was supported from the bottom plate by a guide pin and teflon lining in order to eliminate eccentric motions. Clearances between the rotating cylinder and the holes in the top and bottom plates were 1/16". The cell was made liquid tight by neoprene rubber gaskets placed in the grooves into which the chosen cylindrical lucite tube fitted. By means of a ground glass joint fitting in the top plate a thermometer with a bulb reaching about 3/4" into the cell interior could be inserted. Nipples and vents on the top plate facilitated the filling of the cell. The entire assembly was held together by means of screws and supported by a structure specially designed (see Figure 1) to minimize mechanical vibrations. A 1750 rpm induction motor operated from a regulated 110 A.C. voltage supply was used to drive a Zero-Max variable speed drive (Revco, Inc., Minneapolis, Minn.) with a maximum speed on the output end of 450 rpm. Two sets of pulleys with diameter ratios 1:1 and 1:5 and a V-belt drive between the Zero-Max and the drive shaft of the cell allowed a convenient selection of any speed in the range 0-2200 rpm. Within $\pm$ 1/2 % a set speed remained constant during runs lasting up to 2½ hours. An accurate electric tachometer (Metron Instrum., Inc., Denver, Colo.) was used for rpm measurements. The solid cylinders for these mass transfer studies were formed by melting the solute and casting around a duraluminum spool placed in the interior of a specially designed duraluminum mold. The spool when removed from the mold held the solidified solute in the form of a 5½" long cylinder (see Figure 3). Three molds allowed the casting of cylinders of diameters of 0.81, 1.73 and 2.35 inches.

b. Procedure

Analytical grade Benzoic Acid (Mallincrodt Co.) and trans-Cinnamic Acid (Eastman-Kodak Co.) were used in casting the cylinders. A satisfactorily cast cylinder was machined in a lathe to a given diameter (Figure 3), freed from any loose powder, washed and dried at room temperatures in a dessicator.

The cylinder mounted in the center of the cell was connected to the driving shaft as shown in Figure 1; the cell was rapidly filled with de-aerated distilled water or aqueous glycerol solutions and the rotation started at a preset speed.

The time required for filling (as well as for emptying) the cell was important, since some of the solute could dissolve during this period. With careful preparations this period was reduced to 90-120 seconds during which the cylinder remained stationary. By special filling and emptying tests the amounts dissolved during these periods were determined and suitable corrections applied in the calculation of the rates.

The solvent was introduced into the cell at 25° C. The temperature was maintained within 0.5° C during a run by blowing warm or cool air on the cell. All runs were executed in the range of 24-26°C. The temperature and rotational speed were frequently checked for constancy during a run.

The time of duration of an experiment varied from 15 minutes for high speeds to 150 minutes for low rotational speeds. To assure smooth surfaces in each run it was necessary to cast and machine new cylinders for every experiment.

At the end of a run the cell was rapidly emptied and the volume of the withdrawn liquid carefully measured. From this liquid volume

and the concentration determined by a simple acid-base titration the total amount of benzoic or cinnamic acid dissolved during a run was determined.

Diameters, d_1, of the rotating cylinders used in this study ranged from 1.96 cm to 5.98 cm and the gaps, h, between the rotating and the stationary cylinders varied from 2.07 to 5.96 cm.

c. Method of Calculation

At the beginning of a run, as described in the preceding section, the concentration of the solute in the bulk of the solution, c, is zero. As the experiment proceeds this concentration gradually builds up, until at the end it reaches the value c_f, known from the titration of the liquid withdrawn from the cell. At the interface between the rotating cylinder and the solution the solute concentration is at all times equal to the saturation concentration, c_s. This assumption is justified in view of the work of Noyes and Whitney (21). Thus the mass transfer of the solute dissolving into the solution occurs here under unsteady state conditions with a gradually diminishing concentration difference. Assuming a constant mass transfer coefficient, k_L, defined by the equation

$$N = k_L \Delta c_M \qquad (3)$$

where N = rate, moles/cm^2-sec.

Δc_M = mean concentration difference, moles/cc.

this case becomes analogous to a heat transfer problem in which a log mean of the diminishing temperature driving force is used. Thus

$$\Delta c_M = \frac{\Delta c_i - \Delta c_f}{2.303 \log \frac{\Delta c_i}{\Delta c_f}} \qquad (4)$$

where Δc_f and Δc_i denote the final and initial concentration difference between the interface and solution bulk. In a separate series of experiments the solubilities of cinnamic and benzoic acids were determined in the range of 22-27° C. From these values and the concentration, c_f, determined analytically at the end of each run and the above equation, the values of Δc_M were calculated.

The rate, N, of the dissolution of solids was determined from the amount dissolved (product of solution volume and final concentration, c_f), the interfacial area, A, and the time, t. The mass transfer coefficient, k_L, was then calculated for each run by means of Equation (3).

Densities and viscosities of the benzoic and cinnamic acid solutions were measured (see Appendix) and for diffusivities the data of Chang (5) were used. Average physical properties of the interfacial film were used in the computations. Temperature corrections were applied to all properties to correspond to the actual temperatures of the individual runs.

2. Mass Transfer at Rotating Electrodes

One of the aims of the present study was to find an electrode reaction which would be largely mass transfer controlled, i.e., would involve a small activation energy. Such a reaction would involve a negligible chemical polarization and hence could be used to obtain mass transfer rates by measurements of the polarization of the electrode.

Some reduction-oxidation reactions have long been suggested by several investigators (11)(12)(14) to occur with negligible chemical polarization. Another advantage in using a redox reaction lies in the fact that the electrode surface remains smooth throughout the experiment.

These considerations have led to the selection of the ferri-ferrocyanide couple and nickel electrodes.

An excess of sodium hydroxide was used in order to eliminate the effect of ionic migration (1)(28).

Solutions of potassium ferri- and ferrocyanide and particularly the ferrocyanide, are known to decompose slowly by the action of light resulting in the formation of cyanide and hydroxide ions according to the following equations (13)(19):

$$[Fe(CN)_6]^{-4} + H_2O \underset{\text{dark}}{\overset{\text{light}}{\rightleftharpoons}} [Fe(CN)_5H_2O]^{-3} + CN^-$$

$$CN^- + H_2O \rightleftharpoons HCN + OH^-$$

Solutions used in these studies were freshly prepared for each series of runs in black Jena glass bottles and were never stored for any appreciable time.

a. Apparatus and Procedure

The cell assembly and drive used for the electrolytic experiments were the same as described previously. Three inner nickel electrode rotors (dia. 1.273, 2.48 and 5.024 cm) and three outer cylindrical nickel electrodes (inside dia. 6.07, 9.87, and 13.69 cm), all 15.11 cm long, were used (Figure 2). These offered nine possible geometrical combinations of concentric cylinders with the ratio of the gap to diameter of the inner electrode (h/d_i) ranging from 0.104 to 4.88. The outer electrodes fitted tightly into the lucite cylinders which together with the grooved endplates permitted the assembling of a cell of any of the above-mentioned geometries. Figure 4 shows an example of one of these arrangements. A lucite nipple on the top plate of the assembled cell was screwed into a small tapered hole which on the

inside of this plate ended with a 1/4 mm diameter and was located at a distance of 2.541 cm from the axis of the cell (Figure 5). Through this hole and a piece of polyethylene tubing a continuous liquid junction led to Reference cell No. 1, equipped with a nickel electrode and filled with the same solution as that in the electrolytic cell (see Figure 5). Reference cell No. 2 was connected with the cell by means of a teflon nipple leading through the center of the lucite cylinder and ending flush with the inner side of the outside electrode with a 1/4 mm hole.

Current was drawn from storage batteries and the electrical connection to the rotating electrode was accomplished by means of a mercury well (W in Figure 5). Figure 5, a schematic diagram of the cell and circuit, shows also the connection of the two reference electrodes Nos. 1 and 2 to the cell. The reference electrodes consisted of nickel rods immersed in a solution of the same composition as the bulk liquid in the cell. The ohmic potential drops across the portions of the solution included in the potential measurements were calculated from the conductivity and subtracted. Thus total net polarizations of the electrodes, ΔE_T, were determined at each applied current density, I.

Sodium hydroxide (2 N) was used as the indifferent electrolyte. Potassium ferricyanide and potassium ferrocyanide being present in approximately equal amounts in the concentration range of 0.009 to 0.209 m/L. Solutions prepared from C.P. chemicals (Merck and Co.) were kept in black Jena glass bottles to minimize the effects of light. The analysis for ferricyanide was by means of the iodometric procedure (17) and permanganate titrations (25) were used for ferrocyanide determinations.

The solutions were de-aerated and nitrogen-saturated prior to use to eliminate oxygen, which may introduce appreciable errors, especially in case of low concentrations of the depolarizer. A standard preparation procedure for the nickel electrodes was used throughout all experiments. It consisted of a rouge-paper polishing, a CCl_4 washing and a cathodic treatment in a 5% NaOH solution.

When the cell was assembled, filled and the inner electrode set in rotation at a chosen speed, current was passed and increased by small increments and the potential measured at each setting. From the plateau in the current-potential curve the limiting current densities were evaluated (see Figures 6 and 7). At a given rotational speed each run was first completed with the rotor as the cathode. Then the polarity was reversed and a run was carried out with the rotor as the anode. Speeds used varied from 30 to 1650 rpm. The temperature of 25° C $\pm$ 0.3 was maintained by blowing preheated or precooled air on the outside of the cell.

Physical properties of the solutions were determined in the temperature range of 20-30° C.

Conductivities were measured in a conventional conductivity cell, using a Wheatstone 1000 cycle A.C. bridge.

Viscosities of the solutions relative to water were measured in a thermostat with an Uebelohde pipette, and the absolute viscosities calculated using densities obtained by picknometer determinations

Diffusion coefficients for the ferri- and ferrocyanide ions were measured by means of a capillary method similar to that of Anderson and Saddington (2).

b. <u>Method of Calculation</u>

At limiting current, when the interfacial concentration of the

reacting species becomes zero, the rate of ionic mass transfer of ferricyanide ion to the cathode or of ferrocyanide to the anode can be expressed as (28):

$$N = \frac{I_L}{nF}(1 - t_i) = k_L \cdot c_0 \qquad (5)$$

where I_L = cathodic (I_c) or anodic (I_a) limiting current density, amps/cm^2

n = valence charge of reacting ion

F = the Faraday constant

c_0 = bulk concentration of reacting ion, moles/cc.

t_i = transference number of the reacting ion

k_L = average mass transfer coefficient, cm/sec.

Since the transference numbers of ferri- and ferrocyanide ions did not exceed 0.031 (and were usually much lower) due to the large excess of NaOH used as the indifferent electrolyte, their migration may be neglected and Equation (5) rewritten as

$$N = \frac{I_L}{nF} = k_L c_0 \qquad (5a)$$

Thus by means of Equation (5a) the average mass transfer coefficient, k_c, for ferricyanide reduction, and k_a for ferrocyanide oxidation were calculated for each run. These were tabulated as dimensionless groups k_c/V and k_a/V where V denotes the peripheral velocity at the rotating electrode surface.

From the measured values of viscosity, μ, density, ρ, and diffusion coefficients D_{ferri} and D_{ferro}, corrected to the temperature of a given run, the corresponding Schmidt groups, $Sc = \mu/\rho D$ were computed for the anodic and cathodic experiments.

The two kinds of Reynolds numbers were calculated. One based on the gap, h, between the two cylindrical electrodes was defined:

$$R_h = \frac{V \cdot h}{\nu} \qquad (6)$$

where V = peripheral velocity, cm/sec.

$h = \frac{d_o - d_i}{2}$ = gap between the cylindrical electrodes, cm.

ν = kinematic viscosity, cm^2/sec.

The other was based on the diameter, d_i, of the inner rotating electrode and defined as:

$$R_d = \frac{V \cdot d_i}{\nu} \qquad (7)$$

III. RESULTS AND DISCUSSION

a.) Nature of Flow

The hydrodynamic aspects of the flow between rotating concentric cylinders have been investigated by Taylor (26), who obtained an equation for the stability limit of the laminar flow as a function of the gap to radius ratio, h/r_i, kinematic viscosity, ν, and the Reynolds number, R_h, based on the gap, h, between the cylinders. The smaller this gap, the higher the limit for speeds up to which the flow remains laminar. Calculations for the two geometrical arrangements of cells used in these studies with the two smallest h/r_i ratios, namely 0.2082 and 0.9645 (for the largest rotor used, r_i = 2.512 cm) showed stability limits of 8.64 rpm and 1.57 rpm respectively. This means that even in case of the smallest gap used (h = 0.523 cm), it would be necessary to go down to speeds below 8.64 rpm to secure laminar flow. However, at these low rotational speeds the contribution of natural convection to the rate of mass transfer would obscure that of forced convection produced by rotation. Thus in order to make negligible the effects of a superimposed natural convection, all studies were carried out under conditions of a well developed turbulence. In special experiments, involving injection

of dyes into the fluid during the rotation, fully developed turbulence was observed at the lowest speeds used in these studies.

b.) Characteristic Length Dimension in the Reynolds Number

In the initial phase of the mass transfer studies it was important to decide whether the diameter, d_i, of the rotor or the gap, h, between the cylinders was the characteristic length dimension entering the Reynolds number which describes the nature of the flow. Taylor (26), who studied streamline flow and its stability, based the Reynolds number on the gap. Since all experiments performed in these studies were in region of turbulent flow the problem of the characteristic length appeared to be of first importance.

The problem was solved by an analysis of the mass transfer data obtained for dissolution of benzoic acid into water (Tables 1, 2 and 3) as outlined in the following discussion.

In predicting mass transfer coefficients in the turbulent region, Chilton and Colburn extended the analogy between heat transfer and fluid friction (7) to include mass transfer (6). Expressed in terms of dimensionless groups the equation can be written as:

$$j_D = \frac{k_L}{V} Sc^{2/3} = f/2 = g(Re) \qquad (8)$$

where k_L - mass transfer coefficient, cm/sec

V - peripheral velocity at rotor surface, cm/sec

Sc - Schmidt number

f - friction factor

g(Re) - a function of Re number

$Re = \frac{V \cdot l}{\nu}$, Reynolds number

l - characteristic length dimension in Re number

Assuming at first the gap, h, to be the important length dimension, the data for benzoic acid were plotted in Fig. 8 as j_D

against $R_h = V \cdot h/\nu$. As can be seen from this log-log plot, the data for experimental series, with varying values of the gap to rotor diameter ratios (h/d_i), grouped along separate parallel lines with the slopes of - 0.30. This suggested that in terms of R_h, j_D, the mass transfer parameter must be expressed as:

$$j_D = \text{const } (R_h)^{-0.30} g'(h/d_i) \qquad (9)$$

To find the nature of the function $g'(h/d_i)$ a crossplot of Fig. 8 was prepared at several values of R_h. As shown in Fig. 9 at any given R_h, j_D increases with the +0.3 power the h/d_i ratio. Thus from equation (9)

$$j_D = \text{const} \left(\frac{V \cdot h}{\nu}\right)^{-0.30} \left(\frac{h}{d_i}\right)^{+0.30} = \text{const } \left(\frac{V d_i}{\nu}\right)^{-0.30}$$

$$= \text{const } (R_d)^{-0.30} \qquad (10) \ (*)$$

Hence the mass transfer data should correlate best with a Reynolds number based on the rotor diameter. Indeed as shown in Fig. 10 a single line was obtained in a plot of j_D against $R_d = V \cdot d_i/\nu$.

The conclusion that in turbulent flow the effect of the gap vanishes is further substantiated by Wendt's findings (29) according to which the frictional drag for unstable flow produced by the inner rotor is independent of the gap. This must have been also the conclusion of Theodorsen and Regier (27) who measured drag coefficients on rotating cylinders in a variety of fluids and correlated them with the Reynolds number based on the radius of the rotor.

(*) It should be noted at this point that Chilton-Colburn's j_D-parameter was used only for a preliminary exploration of the nature of the Reynolds number involved. As shown further, the actual correlation of the mass transfer data was based on a modified j_D-parameter. Also the functional dependence on the R_d as given by equation (10) must be regarded as an approximation which was useful in the above mentioned investigation.

c.) Effect of the Schmidt Number

The Schmidt number values ranged in this study from 835 to 11,490. In a plot of k_L/V against R_d, parallel but separate curves were obtained for each of the investigated systems, as shown in Fig. 11 where the curves are shown with the corresponding average Sc values of the systems. The functional dependence of the mass transfer coefficient on the physical properties of the system as represented by the Schmidt number was obtained by a crossplot of Fig. 11 at various values of the Reynolds number shown in Fig. 12. The results lead to the conclusion that

$$\frac{k_L}{V} Sc^{0.644} = \text{const } g(R_d) \qquad (11)$$

where $g(R_d)$ represents a function of the Reynolds number, R_d.

For further mass transfer correlations a new parameter was therefore defined as follows:

$$j_D' = \frac{k}{V} Sc^{0.644} \ (*) \qquad (12)$$

It should be pointed out that the exponent of 2/3 employed by Chilton and Colburn (6) was not based on diffusion data, it was chosen by a successful correlation of early heat transfer data. Mass transfer data were scarce at that time and represented systems with Schmidt values close to unity. A substantial extension of the Sc-range to values of 1,000-3,000 was made by Linton and Sherwood (18), who studied dissolution of solids in flow through round tubes, past

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(*) Strictly speaking the j_D' definition should include a "film factor" (30, 31) accounting for the volume change in the course of reaction. For the electrode reactions there is no net volume change while for the solid dissolution the volume change is negligible so that in both cases the film factor can be taken as unity.

flat plates and other shapes. They reported an agreement with the Chilton-Colburn relation within 40%. The present study includes Schmidt numbers from 835 to 11,490. The simplicity of the present correlating j_D' parameter (equation 10) and its closeness to Chilton-Colburn's j_D is rather remarkable in view of the uncertain empirical basis of the latter.

A more precise investigation of the relation between mass transfer rates and fluid friction such as were developed for flow in tubes and past flat plates by Prandtl, Murphree, von Karman, Reichardt and others (8) may involve serious difficulties for the case of rotating cylinders, in view of the findings of Pai Shi- I (22). From a study of turbulent air flow between rotating coaxial cylinders he concluded that the turbulent flow in the gap cannot be considered two dimensional. A peculiar type of secondary motion consisting of three-dimensional ring-shape vortices takes place. The number of these vortices depends on the rotational speed. This secondary motion has an essential part in the momentum transfer and is responsible for the lack of a homologous turbulence, which would be necessary for any precise mass and momentum transfer analysis.

d.) The General Mass Transfer Correlation

The mass transfer data for three solid dissolution systems and two electrolytic reactions in five solutions of various concentrations were correlated according to the relation:

$$j_D' = \frac{k}{v} Sc^{0.644} = g(R_d) \qquad (13)$$

Individual log-log plots of j_D' versus R_d for the five systems were prepared in order to determine the functional dependence on the Reynolds number.

The data for benzoic acid dissolution into water, shown in Fig. 13, represent experiments with three nominal rotor diameters ranging from 1.94 to 5.98 cm with Series I (diameter of outside cylinder, d_o = 13.86 cm) and Series II (d_o = 10.10 cm). They correlated well in the log-log plot of j_D' versus R_d with an average scattering of $\pm$ 7.5%. The maximum deviation (one point in the region of low R_d values) is + 28%. In view of the wide range of Reynolds numbers studied (239 to 241,000) the results appear satisfactory within the limitations of experimental error.

Figs. 14 and 15 show the same correlation for benzoic acid dissolution into 3.65 molar (G-II) and 4.44 molar (G-I) glycerol-water solutions respectively. These systems with average Schmidt numbers 5,050 and 10,910 were studied over the Reynolds number range of 786 to 48,800. An average scattering of $\pm$ 3.5% with a maximum deviation of +9% was obtained for the 3.65 molar solution. In the more viscous 4.44 molar glycerol-water solution, the average and maximum deviations were $\pm$ 5% and +13% respectively.

Experiments for cinnamic acid dissolutions into water yielded rather unsatisfactory results. The solubility of cinnamic acid in water is very slight (see Appendix), any errors in the analysis for the amount dissolved could cause serious errors in the calculation of the driving force Δc_M (equation 4) and consequently in the value of the mass transfer coefficient k_L. Because of limitations in space the data for cinnamic acid were not presented here.

The mass transfer correlation for the two electrolytic reactions, cathodic reduction of ferricyanide and anodic oxidation of ferrocyanide, for five different concentrations are shown in Figs. 16 and 17. The data for ferricyanide (Schmidt number range

2,230-3,130) show an average deviation of ± 7% and a maximum deviation of 18.5% from the correlating curve. The ferrocyanide system (Schmidt number range 2,590-3,650) correlates with an average deviation of ± 6.6%, the maximum being close to 18%. The range of Reynolds numbers covered by the electrolytic system is 112 to 162,000.

A survey of the correlations of the individual system suggests that in the Reynolds number range of 1,000 to 100,000 the curves in the log-log j_D' versus R_d plots can be approximated by straight lines with a -0.30 slope. The relation can thus be expressed as:

$$j_D' = \frac{k}{V} Sc^{0.644} \approx \text{const } R_d^{-0.30} \qquad (14a)$$

The average constant of Equation (14a) for the five systems was calculated to be 0.0791.

All data for the above listed systems were plotted together in Figure 18 (without differentiating them individually) and a straight (dashed) line representing the equation:

$$j_D' = \frac{k}{V} Sc^{0.644} = 0.0791\ R_d^{-0.30} \qquad (14b)$$

was drawn in. This line correlates data over the R_d range 1,000-100,000 quite satisfactorily. The solid curve gives, however, a better representation of all data. The average deviation from this general correlating curve is ± 8.3%, the maximum deviation found for one point in the low R_d range is 32%. The general correlation of mass transfer at rotating cylinders is based on over 290 runs for five different systems.

Table A lists the range of property values studied for each individual system. The general correlation thus covers a broad

variation of the geometry (range of gap to diameter ratio 0.104 to 3.377) of the characteristic of flow R_d range 112 to 241,000) and of the physical properties of the system (Sc range 835 to 11,490). The close agreement between the results for electrolysis and for solid dissolution within broad ranges of physical properties and experimental conditions supports the general validity of the method of correlation (See Table B for the coordinates of the j_D' versus R_d curve representing the general correlation).

Previous studies relating to mass transfer at rotating electrodes were limited in scope and can be compared to the present work only in respect to the functional dependence on the rotational speed. Roald and Beck (23) found for rotating magnesium electrodes:

$$k_L = \text{const.}\ v^{0.7} \qquad (15)$$

This is in agreement with the results of the present study since Equation (15) can be shown to follow from Equation (14a) for a given system (constant ν and Sc) and given rotor diameter.

In connection with the mass-momentum transfer analogies such as represented by the Chilton-Colburn relation (Equation 8) it is of interest to compare the j_D' correlation of this work with friction factors derived from measurements of the drag on cylinders rotating in various fluids obtained by Theodorsen and Regier (27). Their von Karman type equation for friction coefficients for smooth cylinders can be written (allowing for changes in definitions and symbols) in explicit form as:

$$\log R_d = \frac{0.1737}{\sqrt{f/2}} - \log \sqrt{f/2} + 0.2979 \qquad (17)$$

A curve representing this equation was drawn in Figure 19, in which the curves best correlating the mass transfer for the five systems of Figures 13, 14, 15, 16 and 17 were also reproduced. A com-

parison of these lines suggests the following conclusions.

(a) The curves representing the mass transfer correlations for the systems studied all exhibit the same functional dependence of j_D' versus R_d as does the friction coefficient, f/2 (Equation 17).

(b) All mass transfer curves lie above and within the limits of the average experimental error involved in the determination of f/2 (these limits are indicated in Figure 19). Thus the mass transfer correlation can be expressed as:

$$j_D' = \frac{k}{V} Sc^{0.644} \approx f/2 \qquad (18)$$

where f/2 is given by Equation (17).

(c) The curves for the dissolution of solids lie above those for the electrolytic experiments and also above the f/2 versus R_d line. Since during an experiment for dissolution of a solid the surface gradually loses its smoothness, an increase in the drag, i.e., in f/2 and therefore also of the j_D' values, is to be expected. Indeed Theodorsen and Regier (27) have found higher f/2 values for cylinders with different degrees of roughness. In the electrolytic experiments involving redox reactions no changes in surface smoothness occur which explains why the corresponding j_D' versus R_d lines lie lower (than those for the solids) and closer to the f/2 line for smooth cylinders.

In the R_d range 1,000-100,000 Equation (17) may be approximated quite closely by

$$f/2 \approx 0.0794\ R_d^{-0.30} \qquad (19)$$

This equation shows that f/2 and j_D' have an almost identical functional dependence on R_d (see Equation 14b). The close agreement of the mass transfer data with friction coefficients, while certainly encouraging in view of the Chilton-Colburn analogy, must be taken with

due caution. The present state of knowledge does not allow an exact analysis of the mass-momentum transfer analogy for the case of a concentric inner cylinder rotating in a viscous fluid.

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NOMENCLATURE

Symbol	Definition	Units
A	Interfacial area for mass transfer.	cm^2
c_c	Concentration of a given species in the bulk of the solution.	moles/cc
c_s	Concentration of saturated solution at the interface of the solid.	moles/cc
c_i	Concentration of reacting ions at the electrode interface.	moles/cc
Δc_M	Log mean of the concentration difference.	moles/cc
c_{ferri}	Bulk concentration of ferricyanide ions.	moles/cc
c_{ferro}	Bulk concentration of ferrocyanide ions	moles/cc
d_i	Diameter of the inner rotating cylinder.	cm
d_o	Diameter of outside stationary cylinder.	cm
D_k	Diffusion coefficient of species k.	cm^2/sec
ΔE_T	Total polarization.	mV
F	Faraday equivalent.	96,500 coulomb/equiv.
h	Gap between the concentric cylinders.	cm
i	Total current.	amps
I	Current density.	mA/cm^2
I_L	Limiting current density, in general.	
I_a	Anodic limiting current density.	mA/cm^2
I_c	Cathodic limiting current density.	mA/cm^2
k	Mass transfer coefficient, generally.	cm/sec
k_a	Mass transfer coefficient at the anode.	cm/sec
k_c	Mass transfer coefficient at the cathode.	cm/sec
k_L	Mass transfer coefficient for solid dissolution	cm/sec
ℓ	Characteristic length in the Reynolds number	cm
L	Height of the rotor	cm

n	Number of electrons exchanged in the electrode reaction.	
N	Rate of mass transfer.	moles/cm²/sec
R	Universal gas constant, 8.313×10^7.	erg/°K-mole
r_o, r_i	Radii of outer and inner cylinders respectively.	cm
S	Rotational speed.	rpm
$S' = \frac{S}{60}$	Rotational speed.	rev/sec
t	Time.	sec
T	Temperature.	°K
V	Peripheral velocity at the Rotating cylinder.	cm/sec

Greek Symbols

Δ	Incremental amount.	
δ	Thickness of diffusion layer.	cm
μ	Dynamic viscosity.	g/cm-sec
ν	Kinematic viscosity.	cm²/sec
ρ	Density.	g/cm³
ω	Angular velocity.	radians/sec

Dimensionless Groups

$j_D = \frac{k_L}{V} Sc^{2/3}$, the Chilton-Colburn mass transfer parameter.

$j_D' = \frac{k}{v} Sc^{0.644}$, mass transfer parameter for rotating cylinders.

$R_h = \frac{V \cdot h}{\nu}$, Reynolds number based on gap between the cylinders.

$R_d = \frac{V \cdot d_i}{\nu}$, Reynolds number based on diameter of rotating inner cylinder.

$Sc = \frac{\nu}{D_k}$, Schmidt number for mass transfer of species k.

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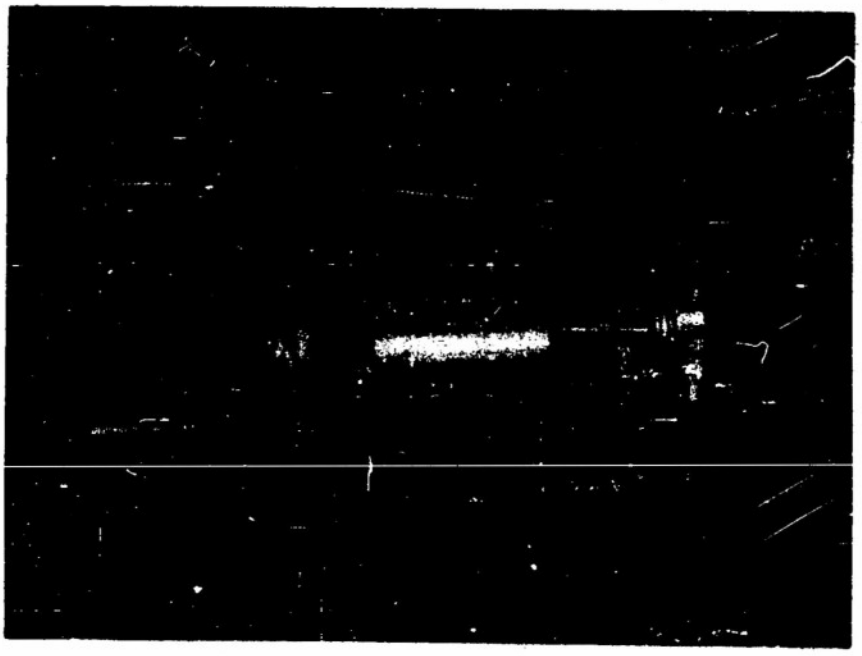

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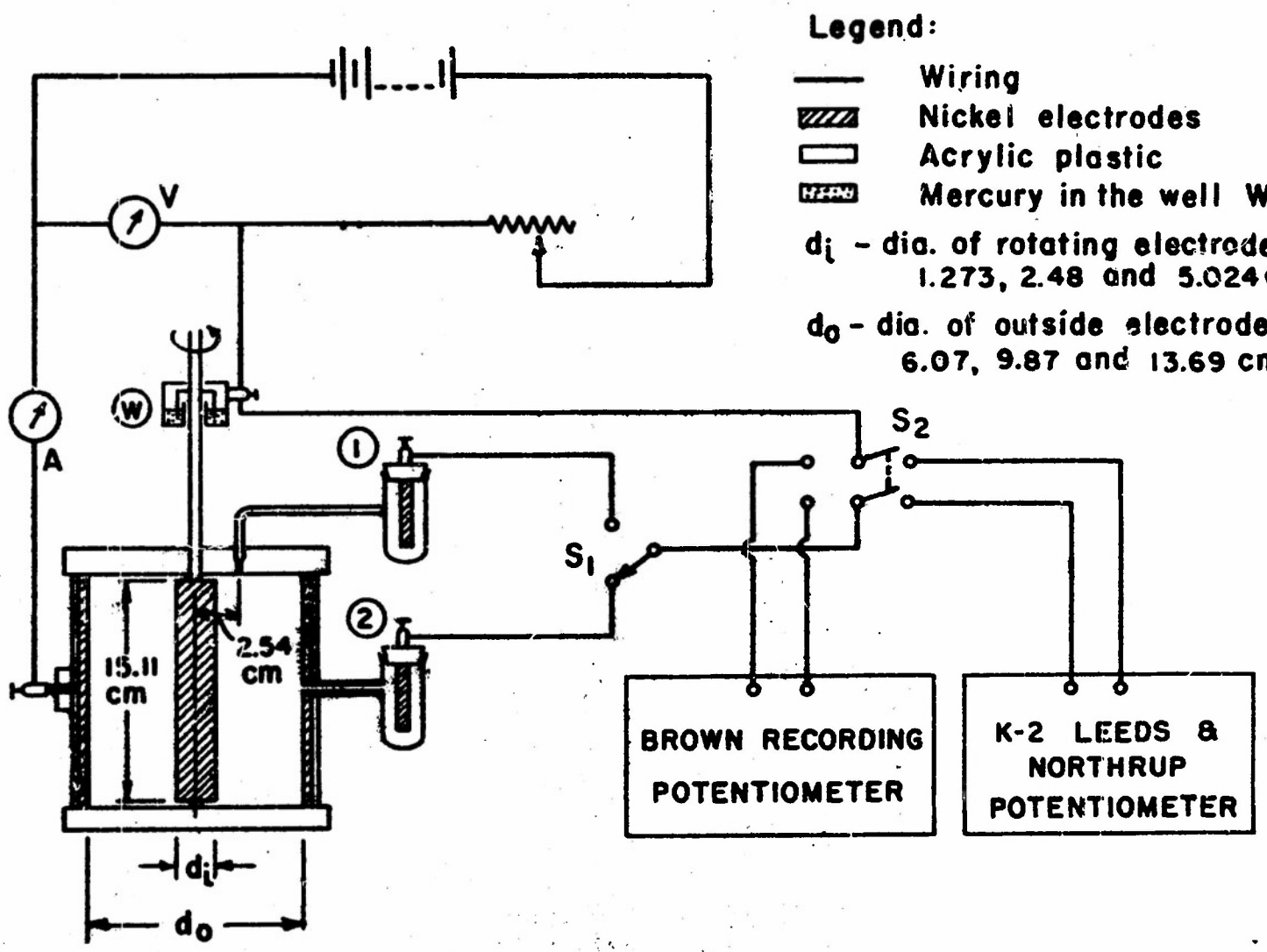

FIG. 5 SCHEMATIC DIAGRAM OF THE ELECROLYSING AND MEASURING CIRCUITS USED WITH THE CELL FOR ROTATING ELECTRODES.

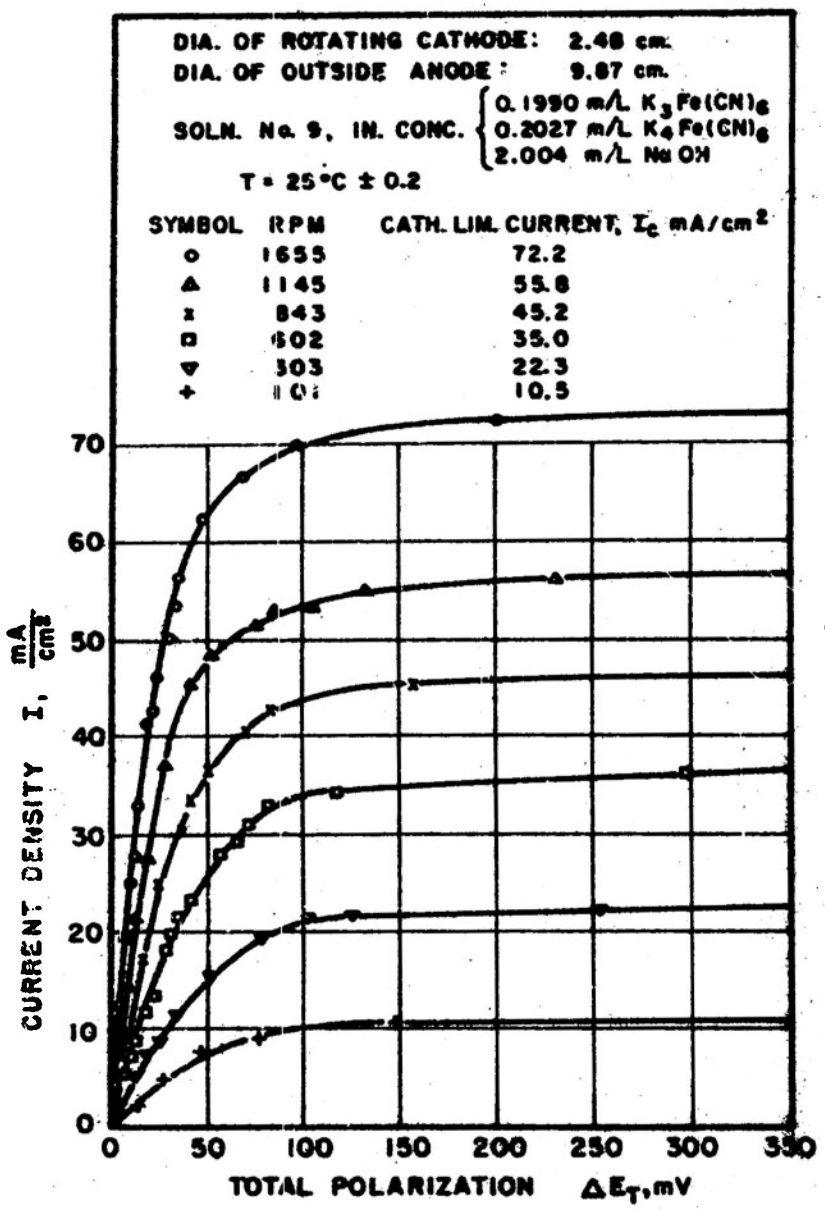

FIG. 6 CATHODIC POLARIZATION CURVES OF FERRICYANIDE ION REDUCTION

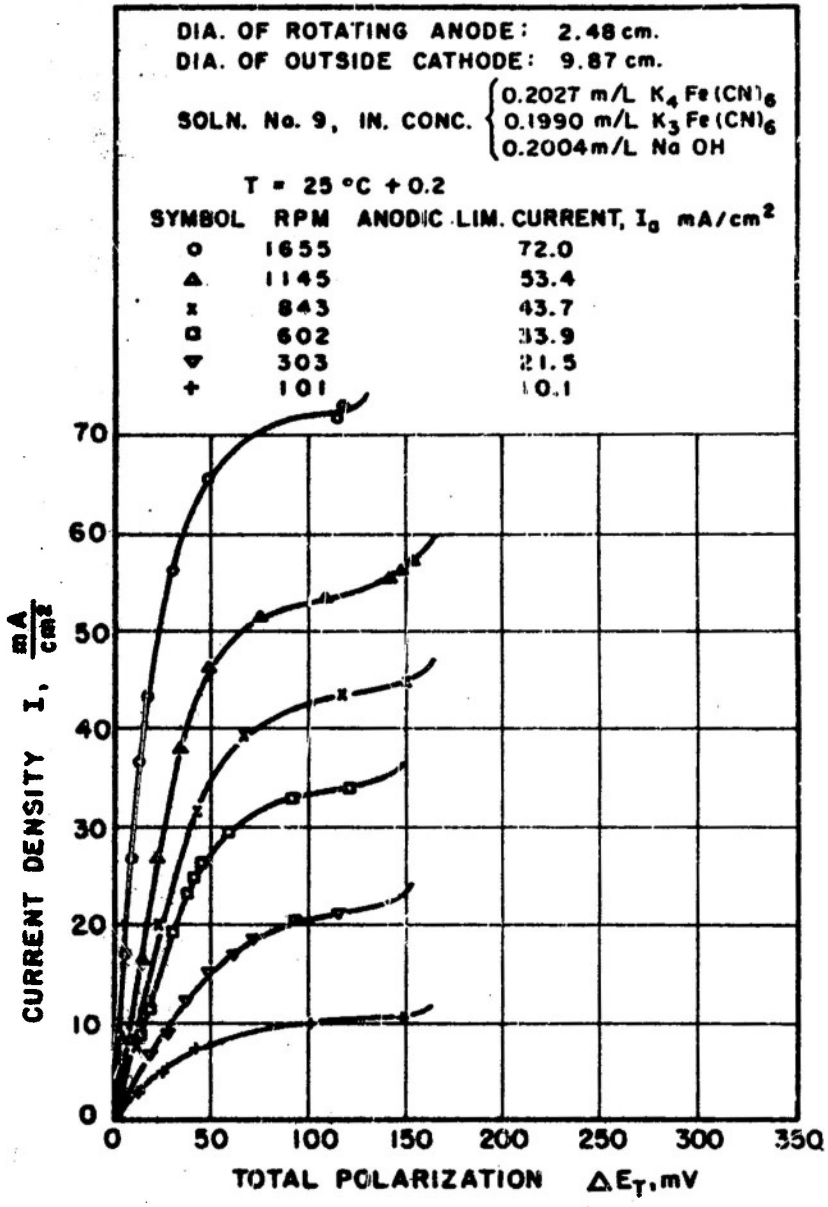

FIG. 7 ANODIC POLARIZATION CURVES OF FERROCYANIDE ION OXIDATION

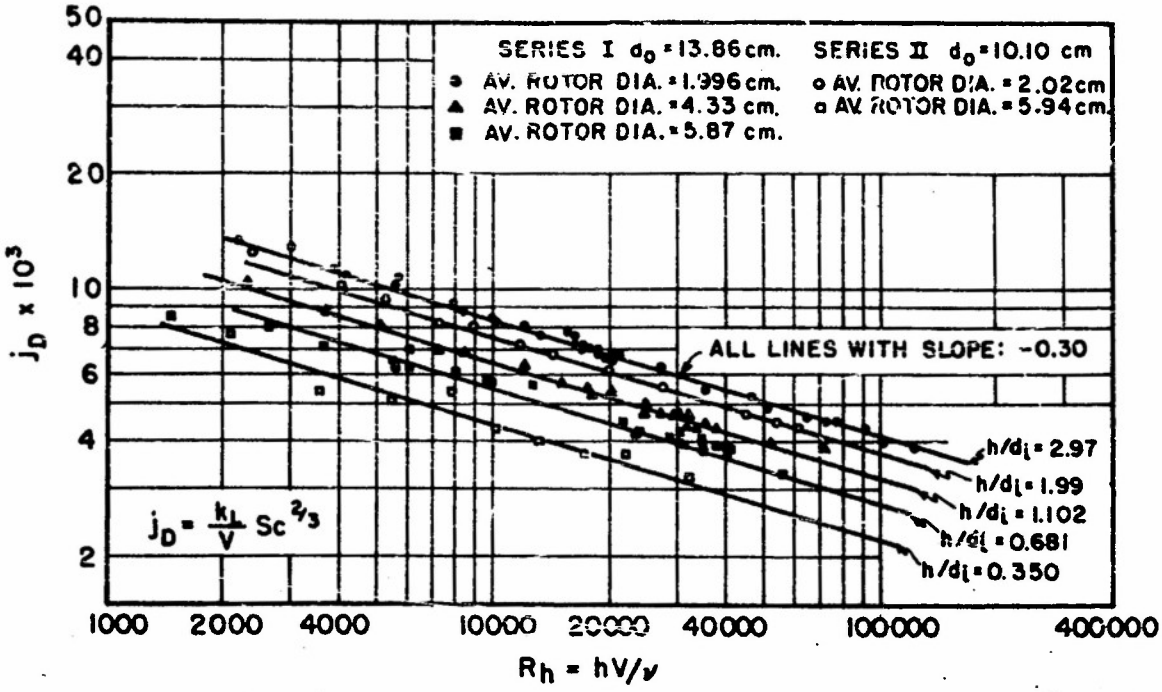

FIG. 8 MASS TRANSFER CORRELATION BASED ON Re-NUMBER $R_h = \frac{Vh}{\nu}$
BENZOIC ACID DISSOLUTION INTO WATER
TEMPERATURE RANGE 23.0-26.6°C

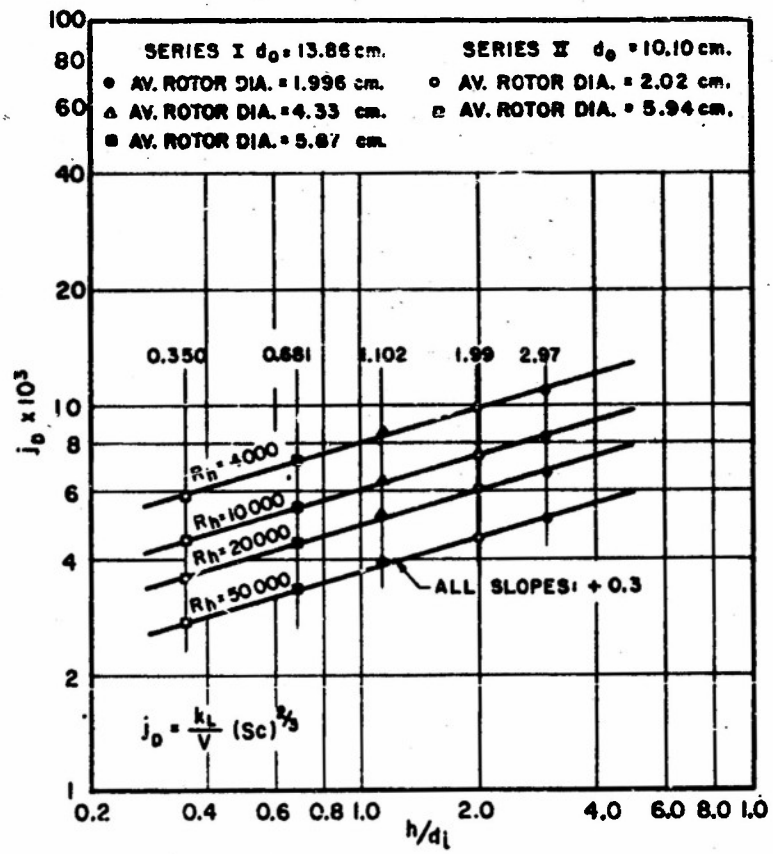

FIG. 9 EFFECT OF GAP TO DIAMETER RATIO h/d_i UPON j_D IN A CORRELATION WITH REYNOLDS NUMBER BASED ON THE GAP.
BENZOIC ACID DISSOLUTION INTO WATER
TEMPERATURE RANGE 23.0 -26.6 °C

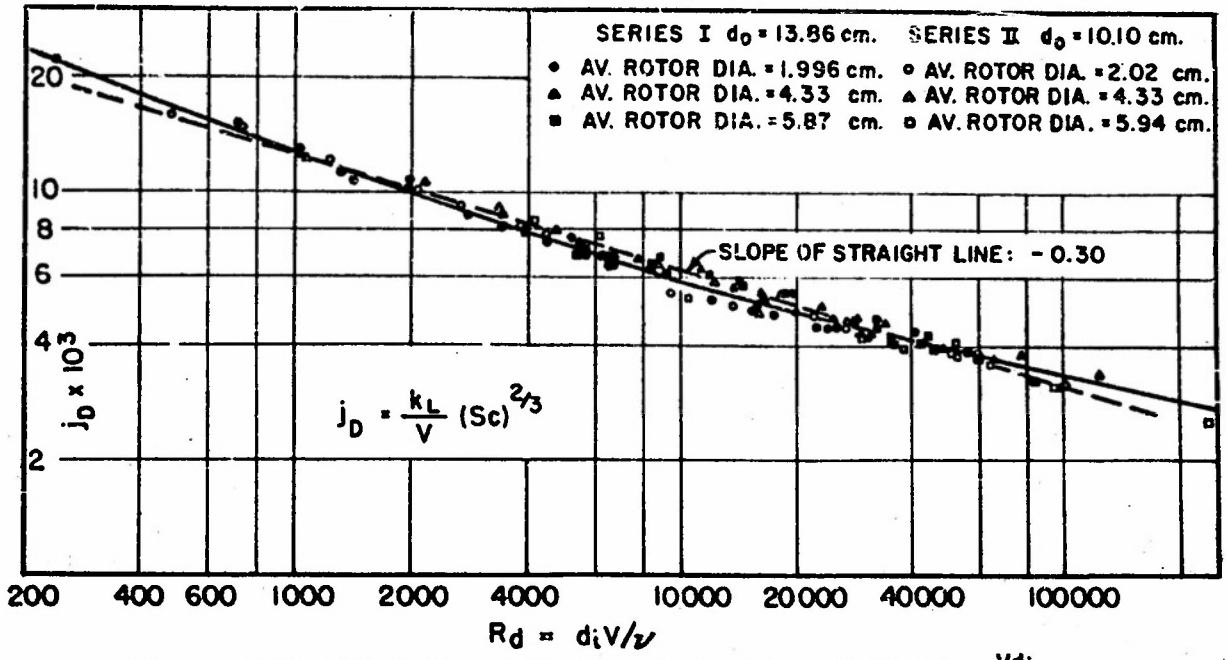

FIG. 10 MASS TRANSFER CORRELATION BASED ON Re-NUMBER $R_d = \frac{Vd_i}{\nu}$
BENZOIC ACID DISSOLUTION INTO WATER

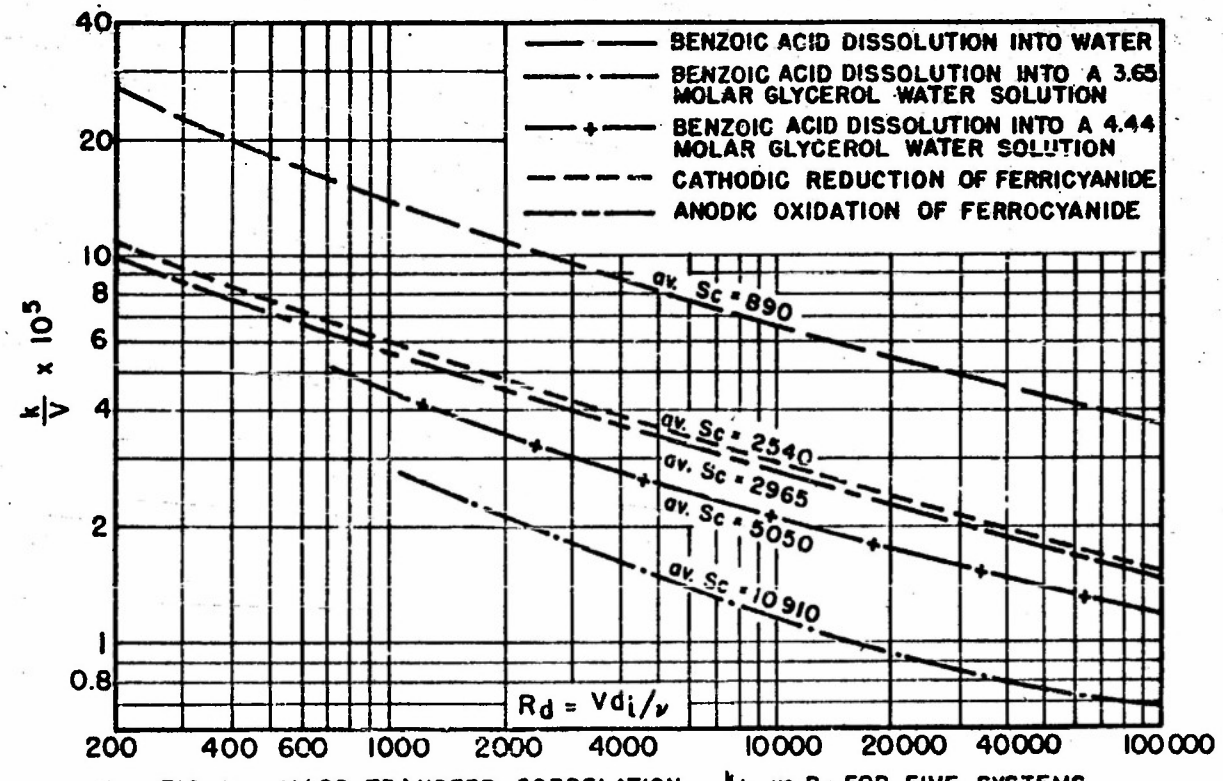

FIG. 11 MASS TRANSFER CORRELATION $k_{/V}$ vs R_d FOR FIVE SYSTEMS

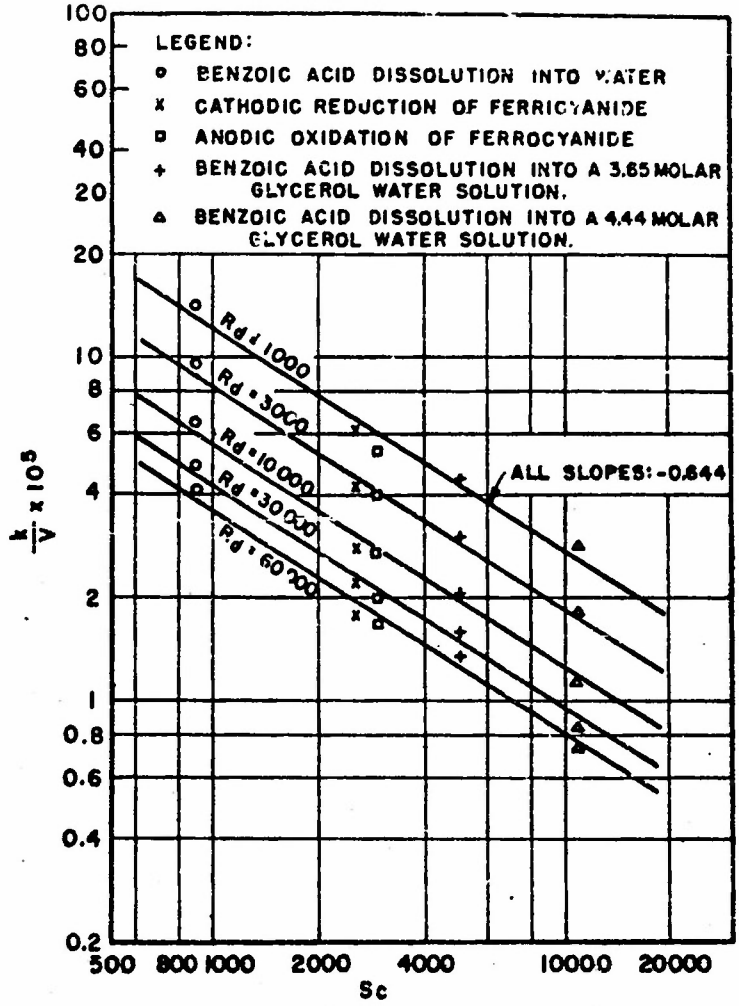

FIG. 12 THE EFFECT OF SCHMIDT NUMBER ON k/V AT VARIOUS REYNOLDS NUMBERS

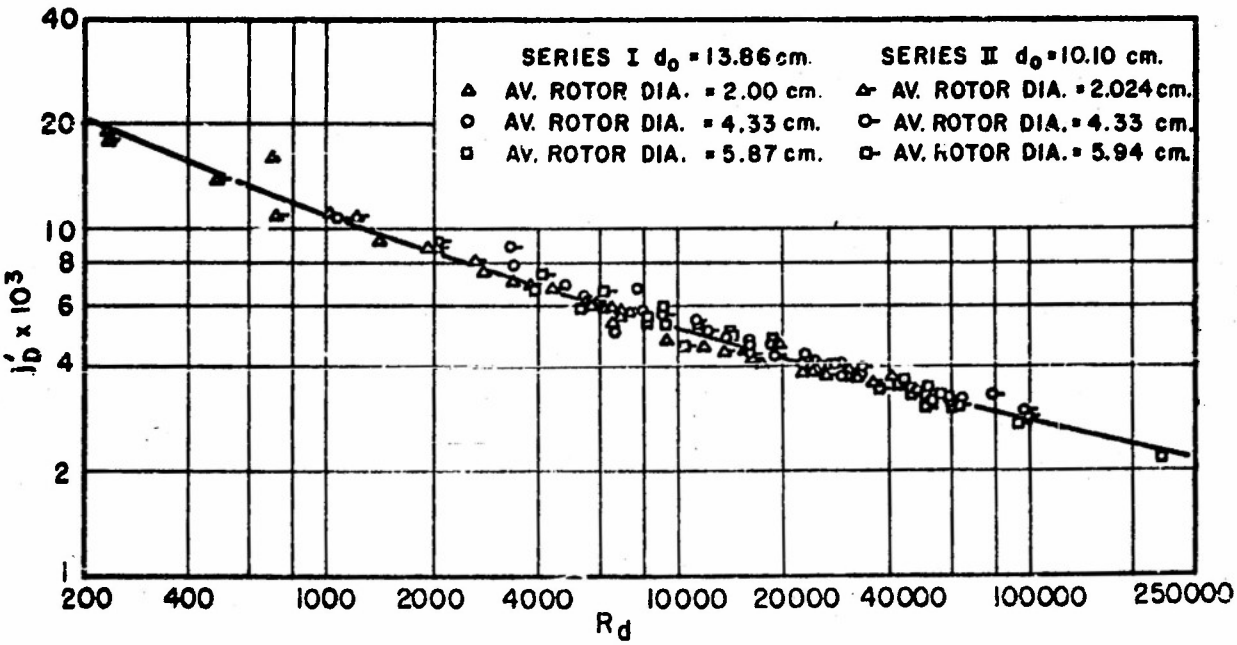

FIG. 13 BENZOIC ACID DISSOLUTION INTO WATER
MASS TRANSFER FROM ROTATING CYLINDERS

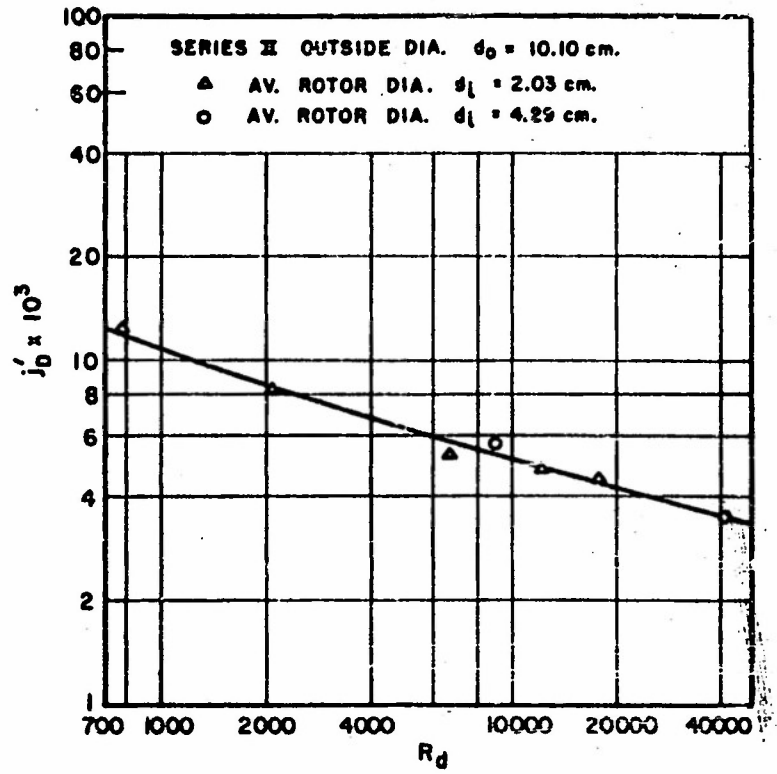

FIG. 14 BENZOIC ACID DISSOLUTION INTO A 3.65 MOLAR GLYCERINE-WATER SOLUTION (G-2)
MASS TRANSFER FROM ROTATING CYLINDERS

$$j'_D = \frac{k_L}{v}(Sc)^{0.644} \text{ vs } R_d$$

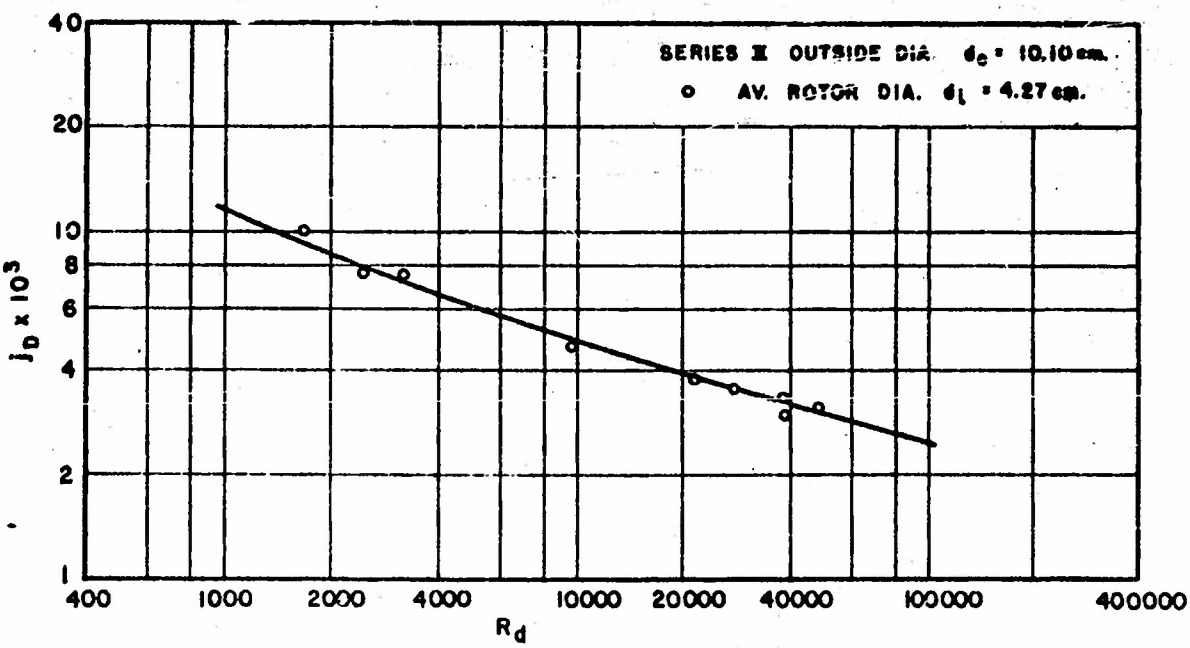

FIG. 15 BENZOIC ACID DISSOLUTION INTO A 4.44 MOLAR GLYCERINE-WATER SOLUTION (G-1)
MASS TRANSFER FROM ROTATING CYLINDERS

$$j'_D = \frac{k_L}{v}(Sc)^{0.644} \text{ vs } R_d$$

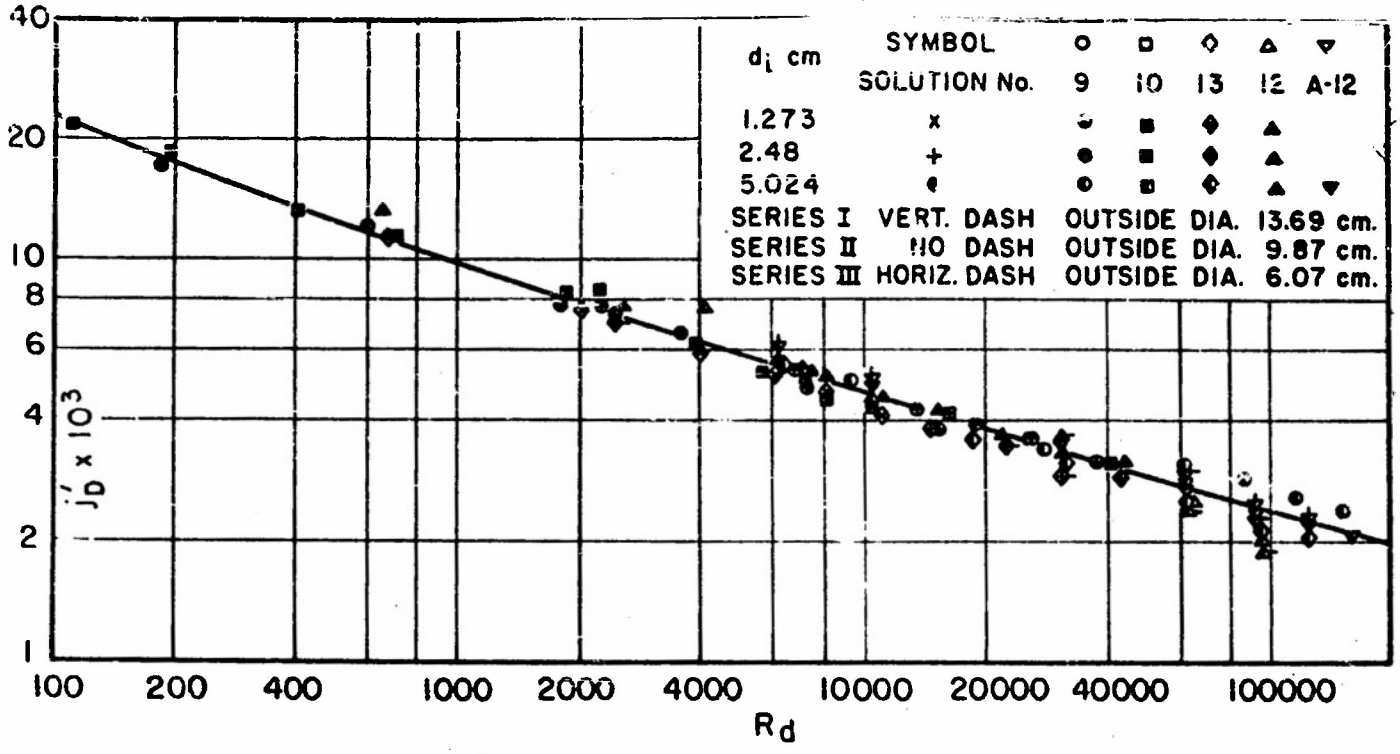

FIG. 16 CATHODIC REDUCTION OF FERRICYANIDE
MASS TRANSFER AT ROTATING ELECTRODES

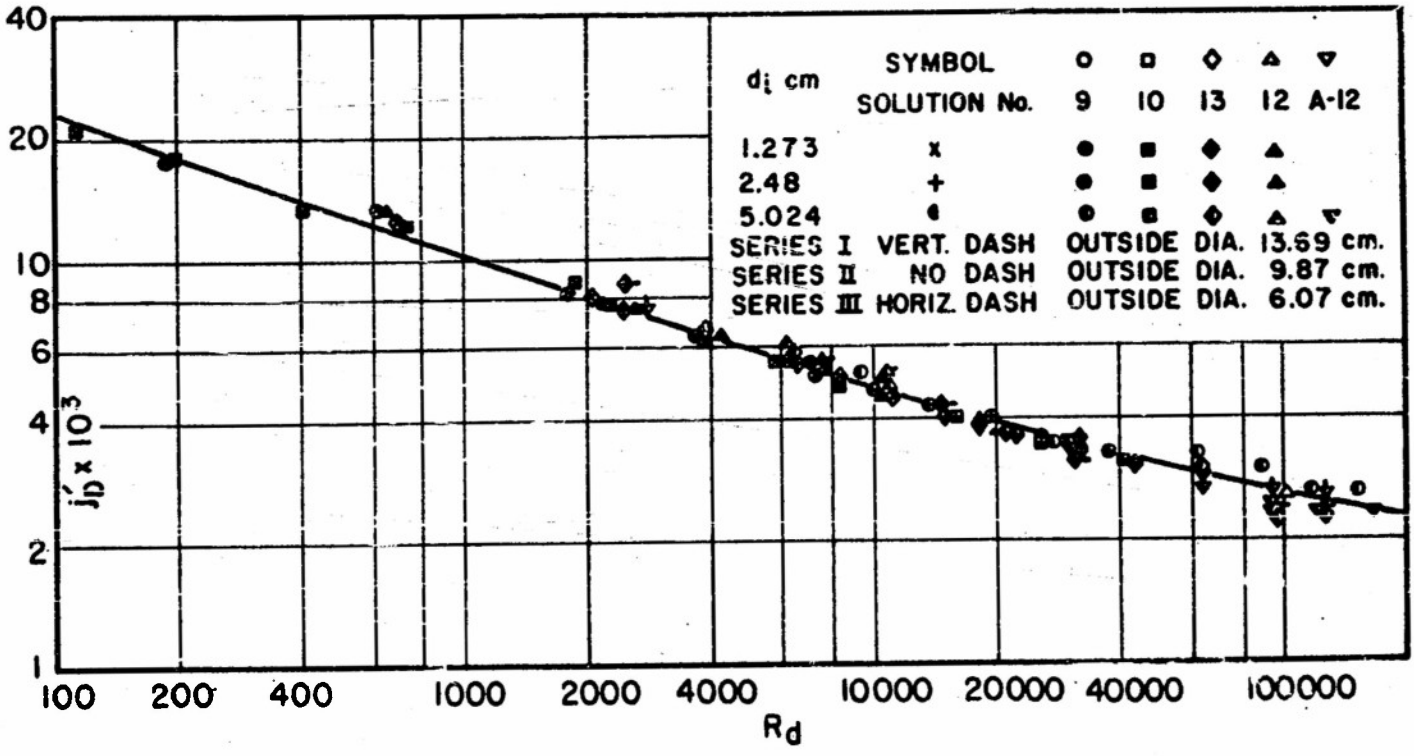

FIG. 17 ANODIC OXIDATION OF FERROCYANIDE
MASS TRANSFER AT ROTATING ELECTRODES

$k_D = 0.644$

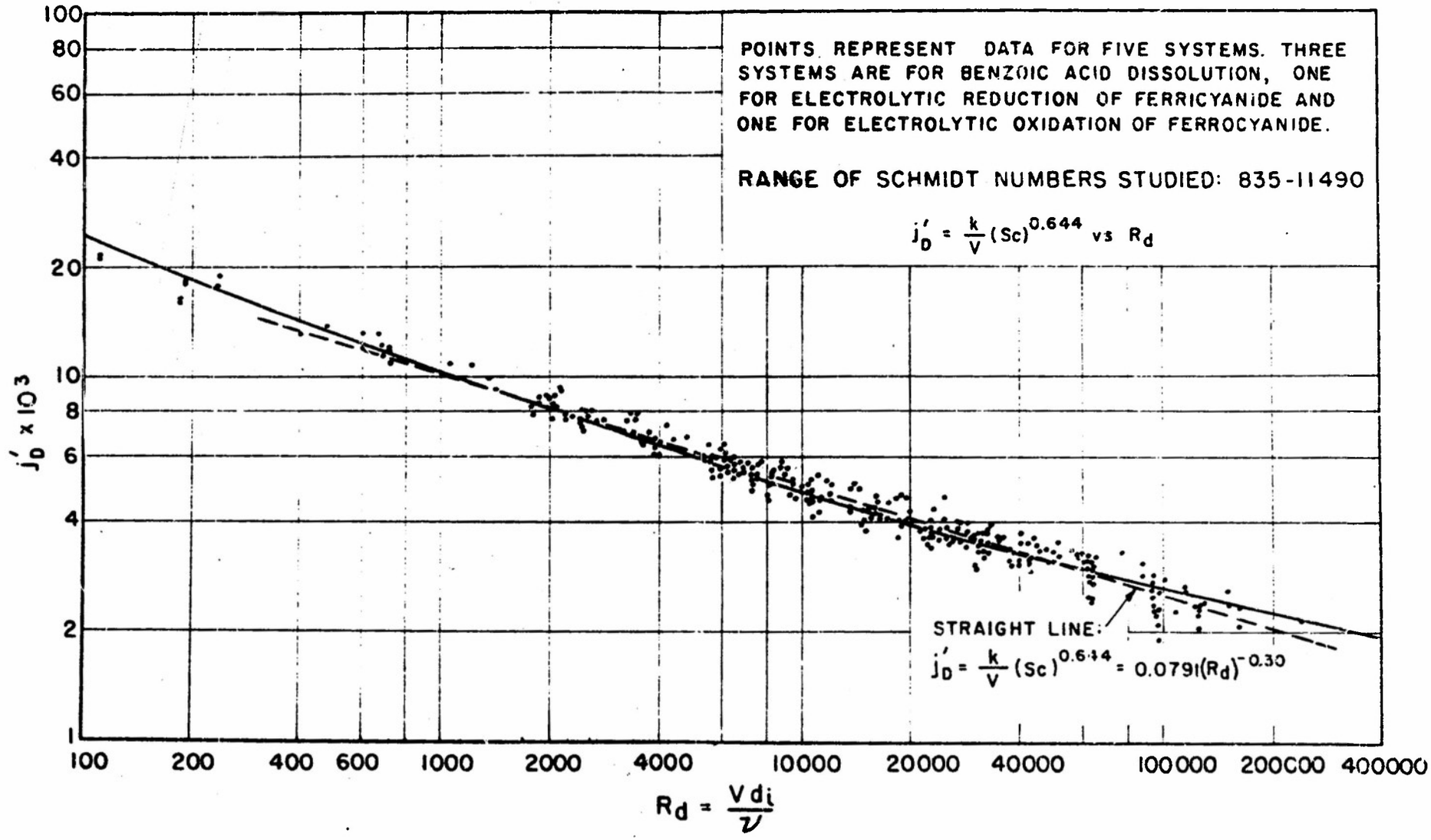

FIG. 18 GENERAL CORRELATION FOR MASS TRANSFER AT ROTATING CYLINDERS

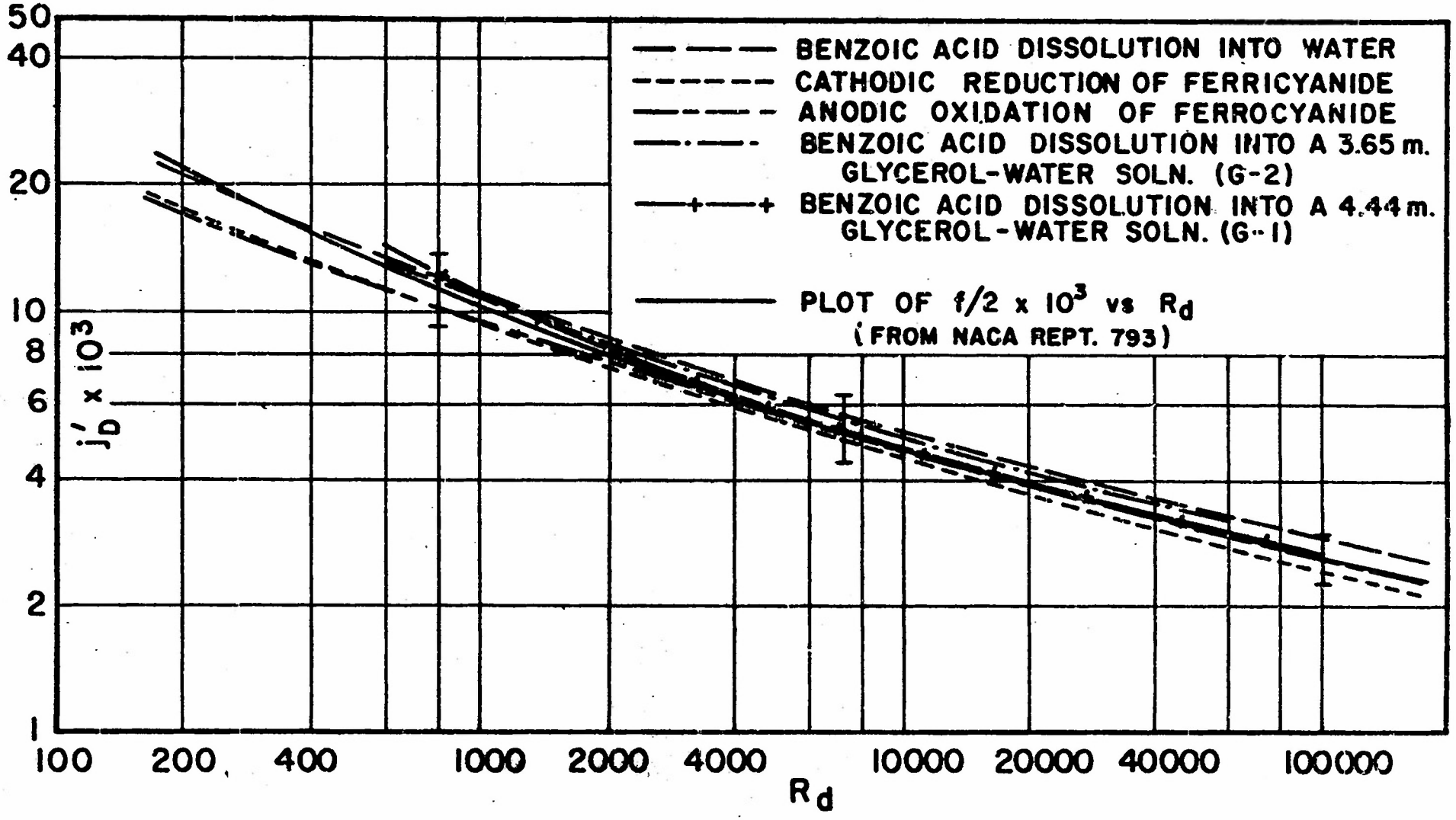

FIG. 19 MASS TRANSFER CORRELATION FOR INNER ROTATING CYLINDER
COMPARISON OF FIVE SYSTEMS STUDIED WITH FRICTION COEFFIENTS f/2

Contract Personnel

Morris Eisenberg	, Research Engineer
A. Hardt	, Laboratory Assistant
J. Worley	, Laboratory Assistant
L. Wolf	, Laboratory Assistant
Charles W. Tobias	, Project Co-director
Charles R. Wilke	, Project Co-director

Table 1a. Benzoic Acid Dissolution into Water. Av. rotor dia. 2.00 cm.

Mass Transfer from rotating cylinders.

Series I; outside dia: d_o = 13.86 cm. Rotor height L = 14.13 cm.

Run No.	d_i cm	V cm/sec	T °C	Rate $N \times 10^8$ mol/cm^{2}sec	$k_L \cdot 10^3$ cm./sec	$\nu_{av} \times 10^2$ cm^2/sec	$D \cdot 10^5$ cm^2/sec	Sc	$j'_D \times 10^3$	R_d
B	1.98	1.057	26.20	0.7299	0.2615	0.8747	1.031	848.9	19.00	239.3
17B	2.00	3.152	25.40	1.573	0.5212	0.8868	1.014	876.7	16.02	709.3
5B	2.02	4.474	25.80	1.652	0.6373	0.8816	1.023	862.1	11.08	1025
11B	2.00	6.294	24.90	1.877	0.7274	0.8981	1.003	895.8	9.205	1402
2B	2.05	8.544	25.10	2.342	0.9431	0.8942	1.007	888.0	8.741	1959
12B	1.97	12.72	25.00	3.042	1.197	0.8961	1.005	891.8	7.470	2796
4BR	1.98	15.22	25.40	3.4321	1.349	0.8888	1.014	876.7	6.961	3391
8BR	1.99	24.35	25.70	4.856	1.895	0.8834	1.020	865.7	6.064	5486
10BR	1.94	25.26	26.40	5.299	2.012	0.8710	1.035	841.5	6.091	5626
10B	1.96	25.66	25.10	4.828	1.905	0.8941	1.007	887.9	5.878	5625
10BX	1.97	25.95	25.60	5.0731	1.988	0.8854	1.018	869.6	5.985	5774
8BX	2.02	28.08	25.50	5.303	2.124	0.8871	1.016	873.1	5.923	6394
9BR	1.94	28.59	25.00	5.269	2.105	0.8971	1.005	891.8	5.846	6183
13BR	1.95	30.43	25.80	5.894	2.271	0.8816	1.023	862.1	5.796	6731
13B	1.94	30.54	26.60	5.930	2.224	0.8676	1.039	835.2	5.545	6829
19B	1.99	42.53	24.30	5.848	2.487	0.9099	0.9892	919.8	4.737	9302
20B	2.00	53.21	24.90	7.152	3.047	0.8981	1.003	895.8	4.560	11,850
21B	1.99	68.47	25.80	9.144	3.845	0.8816	1.023	862.1	4.363	15,460
22B	1.99	76.92	25.30	9.542	4.020	0.8912	1.012	881.0	4.117	17,180
23B	1.99	86.84	25.70	12.72	5.284	0.8834	1.020	865.7	4.708	19,560
24B	2.04	98.49	25.60	11.63	4.850	0.8854	1.018	869.6	3.847	22,690
25B	1.97	107.5	25.60	12.45	5.232	0.8854	1.018	869.6	3.801	23,930
26B	1.96	114.1	25.60	13.62	5.665	0.8854	1.018	869.6	3.880	25,250
28B	2.07	138.7	25.80	15.49	6.564	0.8924	1.009	884.3	3.736	32,180
30B	2.07	173.2	24.90	22.35	8.207	0.8921	1.003	895.8	3.774	40,200

Table 1b. Benzoic Acid Dissolution into Water. Av. rotor dia: d_i = 2.02 cm.

Mass Transfer from Rotating Cylinders

Series II; outside dia: d_o = 10.10 cm. Rotor height L = 14.13 cm.

Run No.	d_i cm	V cm/sec	T °C	Rate $N \times 10^8$ mole/cm.^{2}sec.	$k_L \times 10^3$ cm/sec.	$\nu_{av} \times 10^2$ cm^2/sec	$D \times 10^5$ cm^2/sec	Sc	$j'_D \times 10^3$	R_d
1B	2.04	1.06	24.1	0.5986	0.2310	0.9140	0.9848	928.1	17.80	235.9
2B	2.02	2.07	26.2	1.011	0.3717	0.8747	1.031	848.9	13.79	478.7
3B	2.01	3.17	25.6	1.376	0.5230	0.8854	1.018	869.6	10.98	719.2
4B	2.05	5.24	25.7	1.9214	0.7314	0.8834	1.020	865.7	10.98	1216
5B	2.03	8.90	25.6	2.526	0.9868	0.8854	1.018	869.6	8.664	2040
6B	2.01	11.5	26.6	3.205	1.207	0.8676	1.039	835.2	8.015	2655
7B	2.05	15.9	26.6	3.805	1.451	0.8676	1.039	835.2	6.930	3766
8B	2.02	18.9	26.5	4.366	1.683	0.8694	1.037	838.4	6.791	4396
9B	2.04	25.7	25.8	5.124	2.047	0.8816	1.023	862.1	6.178	5956
10B	2.00	31.3	25.4	5.666	2.302	0.8888	1.014	876.7	5.777	7043
11B	2.09	56.1	26.6	6.304	3.213	0.8676	1.039	835.2	4.360	13510
12B	1.99	72.9	25.6	7.693	3.913	0.8854	1.018	869.6	4.191	16390
13B	2.09	99.6	26.6	10.51	5.339	0.8676	1.039	835.2	4.082	23980
14BR	2.00	117.	26.3	12.40	5.818	0.8728	1.033	844.8	3.828	26740
15BR	1.99	137.	24.6	12.94	6.283	0.9038	0.9959	907.5	3.696	30050
16B	2.01	160.	24.9	15.38	7.195	0.8981	1.003	895.8	3.579	35830

$$j'_D = \frac{k_L}{V} Sc^{0.644} \qquad R_d = \frac{Vd_i}{\nu}$$

Table 2a Benzoic Acid Dissolution into Water. Av. rotor dia: d_1 = 4.33 cm.

Mass Transfer from Rotating Cylinders

Series I; outside dia: d_o = 13.86 cm. Rotor height L = 14.15 cm.

Run No.	d_1 cm.	V cm/sec	T °C	Rate $N \times 10^6$ mole/cm^2.sec	$k_L \times 10^3$ cm/sec	$\nu_{av} \times 10^2$ cm^2/sec	$D \times 10^5$ cm^2/sec	Sc	$J'_D \times 10^3$	R_d
1B	4.36	4.357	25.3	1.270	0.5065	0.8912	1.012	881.0	9.154	2141
1AB	4.37	6.867	25.9	1.762	0.6952	0.8800	1.025	869.9	7.884	3420
2B	4.37	9.636	25.2	2.042	0.8374	0.8935	1.008	886.2	6.858	4723
3B	4.35	13.67	24.8	2.436	1.016	0.9001	1.000	899.7	5.060	6606
3BR	4.35	15.98	25.3	2.932	1.190	0.8912	1.012	881.0	5.868	7782
3B	4.28	15.87	25.4	3.330	1.386	0.8888	1.014	876.7	6.759	7642
9B	4.35	23.05	24.9	3.569	1.568	0.8981	1.003	895.8	5.417	11160
10B	4.32	28.52	24.5	4.056	1.716	0.9058	0.9937	911.5	4.844	13600
11BR	4.29	33.00	26.5	4.843	1.954	0.8694	1.037	838.4	4.517	16280
11B	4.30	33.50	24.9	4.676	1.992	0.8981	1.003	895.8	4.756	16040
12B	4.28	38.32	25.2	5.339	2.264	0.8933	1.008	886.0	4.652	18360
5B	4.33	46.36	24.8	6.289	2.656	0.9001	1.000	899.7	4.352	23260
5BR	4.33	47.72	24.2	5.489	2.347	0.9119	0.9870	923.9	3.996	22660
7BR	4.33	51.01	25.2	5.346	2.622	0.8924	1.009	884.3	4.059	24750
7B	4.30	50.88	25.3	5.789	2.997	0.8899	1.012	879.7	4.635	24590
16B	4.33	55.00	25.8	6.836	2.853	0.8816	1.023	862.1	4.030	27010
13BR	4.29	57.95	25.0	6.832	2.925	0.8861	1.005	891.8	4.007	27740
6BR	4.31	58.79	25.8	6.836	2.849	0.8816	1.023	862.1	3.764	28740
6B	4.31	59.06	25.5	7.174	3.063	0.8878	1.015	874.9	4.067	28670
4B	4.34	64.20	24.6	7.048	2.998	0.9038	0.9959	907.5	3.749	30850
15B	4.33	65.50	25.8	7.545	3.203	0.8816	1.023	862.1	3.798	32170
17B	4.33	98.26	25.2	8.050	4.214	0.8924	1.009	884.3	3.387	47680
18B	4.32	134.8	25.1	10.10	5.517	0.8924	1.007	888.0	3.239	65130

$$j'_D = \frac{k_L}{V} Sc^{0.644} \qquad R_d = \frac{V d_1}{\nu}$$

Table 2b. Benzoic Acid Dissolution into Water Av. rotor dia: d_1 = 4.33 cm.

Mass Transfer from Rotating Cylinders

SeriesII; outside dia: d_o = 10.10 cm. Rotor height L = 14.15 cm.

Run No.	d_1 cm	V cm/sec	T °C	Rate $N \times 10^8$ mol/cm^{2}sec	$k_L \times 10^3$ cm/sec	$\nu_{av} \times 10^2$ cm^2/sec	$D \times 10^5$ cm^2/sec	Sc	$j'_D \times 10^3$	R_d
1B	4.36	2.209	24.7	0.7759	0.2982	0.9020	0.9982	903.6	10.87	1065
2B	4.34	4.454	24.6	1.243	0.5125	0.9038	0.9959	907.5	9.243	2139
3B	4.36	6.780	25.6	1.633	0.6785	0.8854	1.018	869.6	7.812	3339
4B	4.34	11.29	24.6	2.098	0.9134	0.9038	0.9959	907.5	6.496	5421
5B	4.34	18.07	24.8	2.831	1.273	0.9001	1.000	899.7	5.627	8715
6B	4.32	25.04	25.4	3.356	1.609	0.8888	1.014	876.7	5.045	12170
7B	4.31	33.35	24.7	3.887	1.781	0.9020	0.9982	903.6	4.275	15940
8B	4.35	41.11	24.8	4.653	2.203	0.9001	1.000	899.7	4.280	19870
9B	4.33	56.34	25.6	5.914	2.863	0.8854	1.018	869.6	3.969	27550
10B	4.30	67.09	26.6	6.987	3.471	0.8676	1.039	832.2	3.938	33250
12B	4.36	157.5	25.5	8.018	6.627	0.8871	1.016	873.1	3.295	77410
13BR	4.26	200.8	25.6	10.29	7.399	0.8854	1.018	869.6	2.879	96610
13B	4.35	200.8	25.6	10.03	7.250	0.8854	1.018	869.6	2.793	99640

$$j'_D = \frac{k_L}{V} Sc^{0.644} \qquad R_d = \frac{V d_1}{\nu}$$

Table 3a Benzoic Acid Dissolution into Water Av. rotor dia: d_1 = 5.87 cm.

Mass Transfer from Rotating Cylinders

Series I, outside dia: d_o = 13.86 cm. Rotor height L = 14.13

Run No.	d_1 cm.	V cm/sec	T °C	Rate N x10^8 mole/cm^{2}sec	k_L x10^3 cm/sec	ν_{av} x10^2 cm^2/sec	D x10^5 cm.^{2}/sec	Sc	j'_D x10^3	R_d
9B	5.89	6.137	23.5	1.801	0.5005	0.9264	0.9716	953.5	6.760	3,902
8BB	5.89	8.574	25.1	1.634	0.6476	0.9442	1.007	888.0	5.980	5,349
10BR	5.96	12.40	25.1	2.077	0.8691	0.9442	1.007	888.0	5.550	8,265
10B	5.87	12.60	24.8	2.049	0.8462	0.9001	1.004	896.5	5.350	8,217
1B	5.87	13.62	24.7	2.326	0.9975	0.9020	0.9982	903.6	5.864	8,864
1BX	5.87	13.71	25.3	2.224	0.9240	0.8912	1.018	881.0	5.309	9,030
11B	5.86	18.20	24.5	2.789	1.173	0.9058	0.9937	911.5	5.191	11,770
12B	5.84	21.92	24.6	3.208	1.374	0.9038	0.9959	907.5	5.035	14,090
2B	5.87	22.04	25.1	3.237	1.365	0.8949	1.006	889.6	4.908	14,460
13BR	5.85	28.55	25.6	4.153	1.736	0.8854	1.018	869.6	4.751	18,860
4B	5.85	49.19	24.8	5.457	2.373	0.9001	0.9992	900.8	3.856	31,970
14BR	5.92	51.83	26.5	5.953	2.410	0.8694	1.037	838.4	3.548	35,290
15B	5.87	53.26	25.1	5.466	2.418	0.8942	1.007	888.0	3.594	34,960
19B	5.85	63.47	25.6	6.499	2.842	0.8854	1.018	869.6	3.497	41,940
21BR	5.94	66.47	26.1	6.880	2.928	0.8773	1.029	852.5	3.398	45,010
21B	5.82	67.35	25.3	7.125	3.128	0.8912	1.012	881.0	3.659	43,980
21BX	5.95	67.48	25.9	6.663	2.898	0.8800	1.025	858.7	3.328	45,630
20B	5.85	76.25	25.6	7.415	3.267	0.8854	1.018	869.6	3.347	50,210
6BX	5.91	76.89	25.6	7.324	3.207	0.8854	1.018	869.6	3.254	51,390
3B	5.84	77.77	25.0	7.630	3.406	0.8961	1.006	891.8	3.479	50,870
6BR	5.87	86.06	24.4	7.580	3.534	0.9078	0.9917	915.4	3.315	55,650
5B	5.89	89.28	25.0	8.123	3.654	0.8961	1.006	891.8	3.250	58,680
5BR	5.89	89.96	25.7	8.242	3.610	0.8834	1.020	865.7	3.128	59,980
24B	5.90	91.19	24.0	7.562	3.578	0.9161	0.9826	932.3	3.206	58,730
26B	5.89	124.0	25.7	7.797	4.474	0.8834	1.020	865.7	2.810	82,700
30B	5.87	362.5	25.8	17.67	10.10	0.8816	1.023	862.1	2.165	241,400

Table 3b. Benzoic Acid Dissolution into Water. Av. rotor dia: d_1 = 5.94 cm.

Mass Transfer from Rotating Cylinders

Series II; outside dia: d_o = 10.10 cm. Rotor height L = 14.13 cm.

Run No.	d_1 cm.	V cm/sec	T °C	Rate N x10^8 mol/cm^{2}sec	k_L x10^3 cm.sec	ν_{av} x10^2 cm^2/sec	D x10^5 cm^2/sec	Sc	j'_D x10^3	R_d
2B	5.98	6.210	25.5	1.395	0.5796	0.8871	1.016	873.1	7.310	4,151
3B	5.98	9.331	24.0	1.670	0.7494	0.9161	0.9826	932.3	6.562	6,091
4B	5.96	15.30	24.8	2.840	0.8862	0.9001	1.004	896.5	4.525	10,359
5B	5.96	24.97	23.0	2.594	1.273	0.937	0.9605	975.5	4.288	15,880
7B	5.96	44.25	24.8	3.832	1.996	0.9038	0.9959	907.5	3.622	29,180
8B	5.94	56.79	24.9	4.401	2.434	0.8981	1.003	895.8	3.413	37,560
9B	5.93	73.59	25.8	5.282	2.974	0.8816	1.023	862.1	3.140	49,500
10B	5.90	85.86	26.1	6.112	5.792	0.8773	1.029	852.5	3.112	63,200
11B	5.95	140.7	24.9	6.168	4.826	0.8981	1.003	895.8	2.751	93,230

Table 4 Benzoic Acid Dissolution into 3.65 Molar Glycerine-Water Solution
Mass Transfer from Rotating Cylinders

Run No.	d_1 cm	V cm/sec	T °C	Rate $Nx10^6$ mole/cm^2 sec	$k_L x10^3$ cm/sec	$\nu_{av} x10^2$ cm^2/sec	$Dx10^5$ cm^2/sec	Sc	$j'_D x10^3$	R_d
Table 4a. Av. rotor dia: d_1 = 2.03 cm. Series II; outside dia: d_o = 10.10 cm. Motor height L = 14.15 cm.										
170	2.03	8.089	25.0	1.375	0.4152	2.089	0.4154	5,053	12.45	786
180	2.03	21.27	25.0	2.522	0.7198	2.089	0.4154	5,053	8.214	2,067
140	2.04	68.25	25.0	4.586	1.513	2.089	0.4154	5,053	5.378	6,667
150	2.02	194.1	25.1	7.690	2.462	2.080	0.4154	5,006	4.783	12,058
160	2.05	175.4	25.8	10.57	3.382	2.016	0.4296	4,926	4.581	17,840
Table 4b. Av. rotor dia: d_1 = 4.03 cm. Series II; outside dia: 10.10 cm. Motor height L = 14.15 cm.										
210	4.27	44.11	25.0	2.585	1.027	2.089	0.4154	5,053	5.645	9,017
220	4.30	202.5	25.0	5.979	2.867	2.089	0.4154	5,053	3.459	41,690

Table 5. Benzoic Acid Dissolution into 4.44 Molar Glycerine-Water Solution, Av. rotor dia: d_1 = 4.29 cm.
Mass Transfer from Rotating Cylinders
SeriesII; outside dia: d_o = 10.10 cm. Motor height L = 14.15 cm.

Run No.	d_1 cm	V cm/sec	T °C	Rate $Nx10^6$ mole/cm^2 sec	$k_L x10^3$ cm/sec	$\nu_{av} x10^2$ cm^2/sec	$Dx10^5$ cm^2/sec	Sc	$j'_D x10^3$	R_d
50	4.26	11.64	25.0	1.065	0.2906	3.031	0.2779	10,910	9.935	1,636
90	4.28	17.32	24.6	1.227	0.3233	3.064	0.2744	11,166	7.544	2,420
40	4.27	28.65	24.9	1.499	0.4241	3.039	0.2770	10,970	7.485	3,182
30	4.31	67.43	25.0	2.512	0.7892	3.031	0.2779	10,910	4.643	9,588
10	4.31	148.8	25.1	3.763	1.411	3.025	0.2787	10,860	3.763	21,210
90	4.20	206.5	24.1	5.186	1.789	3.106	0.2702	11,490	3.572	27,900
60	4.30	270.7	24.9	6.410	2.248	3.039	0.2770	10,970	3.320	36,300
100	4.30	277.2	24.4	6.557	2.015	3.080	0.2727	11,290	2.960	38,700
80	4.18	354.6	24.8	8.967	2.801	3.047	0.2762	11,030	3.168	48,770

Tables 6 and 7

Cinnamic Acid Dissolution into Water
Mass Transfer from Rotating Cylinders

Run No.	d_i cm	V cm/sec	T °C	Rate $Nx10^8$ mole/cm²sec	$k_L x10^3$ cm/sec	$\nu_{av} x10^2$ cm²/sec	$Dx10^5$ cm²/sec	Sc	$j'_D x10^3$	R_d
Table 6.Series I; outside dia: d_o=13.86 cm.Av. rotor dia: d_i=1.93cm.Rotor height L=14.13.cm.										
8CR	1.89	29.56	25.2	0.4280	1.506	0.8934	0.9148	976.6	4.996	8,253
1CR	1.95	29.99	25.3	0.4966	1.749	0.8918	0.9170	972.1	4.896	6,561
9CR	1.91	41.42	25.2	0.5876	1.904	0.8934	0.9148	976.6	3.666	8,855
2C	1.94	48.45	24.7	0.5670	1.943	0.9043	0.9026	1002.	3.433	10,390
10CR	1.90	51.91	25.9	0.7148	2.528	0.8799	0.9301	946.0	4.175	11,210
5CR	1.92	63.93	25.8	0.7347	2.541	0.8818	0.9280	950.3	3.028	13,920
6CR	1.91	73.91	25.4	0.8180	3.101	0.8895	0.9192	967.7	3.507	15,870
7CR	1.90	78.08	25.6	0.9659	3.741	0.8857	0.9236	959.1	3.987	16,750
13CR	2.04	120.8	25.4	1.037	4.041	0.8895	0.9192	967.7	2.797	27,700
Table 7. Series I; outside dia: d_o=13.86 cm. Av. rotor dia: d_i=6.90 cm. Motor height L=14.1 cm.										
16CR	5.90	26.50	24.2	0.3779	1.595	0.9130	0.8988	1022.	3.378	17,130
15CR	5.90	147.0	24.8	0.2289	1.238	0.9011	0.9060	994.6	7.176	96,250
3C	5.90	159.5	25.3	0.7866	3.672	0.8914	0.9170	972.1	1.932	106,600
8C	5.90	159.8	25.2	0.8341	3.892	0.8934	0.9148	976.6	2.051	105,800
4C	5.89	210.1	25.4	0.9707	4.960	0.8895	0.9192	967.7	1.976	139,100
2C	5.91	248.7	26.5	1.070	5.601	0.8684	0.9435	920.4	1.870	165,200
6C	5.90	285.4	25.3	1.204	6.553	0.8914	0.9170	972.1	1.527	188,900
17CR	5.90	421.2	24.0	1.678	9.289	0.9207	0.8883	1036.	1.928	259,900

Table 8. Cinnamic Acid Dissolution into Water. Av. rotor dia: d_i = 4.18 cm.
Mass Transfer from Rotating Cylinders

Series I; outside dia: d_o = 13.86 cm. Motor height L = 14.15 cm.

Run No.	d_i cm	V cm/sec	T °C	Rate $Nx10^8$ mole/cm²sec	$k_L x10^3$ cm/sec	$\nu_{av} x10^2$ cm²/sec	$Dx10^5$ cm²/sec	Sc	$j'_D x10^3$	R_d
2C	4.33	24.19	24.6	0.2606	1.006	0.9054	0.9015	1004.	3.563	11,570
23CRX	4.18	86.15	26.4	0.9153	3.719	0.8702	0.9410	924.8	3.509	41,380
25CR	4.18	117.3	26.2	1.120	4.515	0.8741	0.9368	933.1	3.156	56,240
24CR	4.13	126.7	25.2	0.7919	3.514	0.8934	0.9148	976.6	2.201	58,670
17C	4.22	170.3	26.8	1.321	5.991	0.8693	0.9448	920.1	2.850	82,670
26CR	4.12	182.3	25.2	1.125	4.962	0.8934	0.9148	976.6	2.291	84,070
26CRX	4.13	192.9	25.3	1.144	4.814	0.8911	0.9165	972.3	2.096	89,400
24CR	4.28	199.8	24.8	1.154	5.128	0.9011	0.9060	994.6	2.186	94,900
13CRX	4.23	219.9	26.1	1.021	5.382	0.8951	0.9125	980.9	2.066	103,900
14C	4.23	225.2	25.3	1.205	5.662	0.8924	0.9168	973.4	2.112	106,700
18CR	4.19	253.1	25.2	1.560	7.671	0.8934	0.9148	976.6	2.770	129,300
31CR	4.08	250.8	25.7	1.226	6.228	0.8857	0.9263	954.0	2.059	115,900
27CR	4.11	254.2	25.2	1.417	7.220	0.8934	0.9148	976.6	2.381	116,900
29CR	4.10	268.7	24.7	1.484	7.411	0.9051	0.9038	999.2	2.348	122,400
15C	4.23	285.4	25.2	2.151	10.72	0.8934	0.9148	976.6	3.163	156,100

Table 9. Mass Transfer at Rotating Electrodes. Ferri-Ferrocyanide Couple.

Solution No. 12 (1.958 N. NaOH)

Run No.	V cm/sec	T °C	$\nu \times 10^2$ cm²/sec	R_d	Cathodic Reduction of Ferricyanide: $C_{ferri} \times 10^3$ mol/cc	I_c mA/cm²	$k_c \times 10^5$ cm/sec	$D \times 10^5$ cm²/sec	Sc	$j'_D \times 10^3$	Anodic Oxidation of Ferrocyanide: $C_{ferro} \times 10^3$ mol/cc	I_a mA/cm²	$k_a \times 10^5$ cm/sec	$D \times 10^5$ cm²/sec	Sc	$j'_D \times 10^3$
9a. d_i = 1.273; A = 61.2 cm² Ser. II (d_o = 9.87 cm)																
243A	6.75	23.5	1.309	654	-	-	-	-	-	-	0.01011	0.51	52.4	0.451	2.902	13.2
244C	20.86	24.0	1.295	1,992	0.00983	1.10	114.8	0.531	2,439	8.61	-	-	-	-	-	-
246C,247A	41.6	24.7	1.274	4,157	0.00987	1.77	185.4	0.541	2,385	6.62	0.01018	1.65	168.0	0.465	2,739	6.61
248C,249A	61.8	25.0	1.266	6,214	0.00982	2.29	241.3	0.545	2,322	5.74	0.01020	2.07	210.8	0.468	2,705	5.53
250C,251A	82.1	25.0	1.266	8,155	0.00978	2.78	294.5	0.545	2,322	5.28	0.01023	2.55	258.0	0.468	2,705	5.10
252C,253A	111.7	25.0	1.266	11,230	0.00976	3.36	356.0	0.545	2,322	4.69	0.01028	3.18	321.0	0.468	2,705	4.66
9b. d_i = 2.48 cm, A = 117.6 cm² Ser. II (d_o = 9.87 cm)																
103C,110A	13.0	25.0	1.266	2,547	0.00998	0.66	68.6	0.545	2,323	7.78	0.01011	0.60	61.3	0.468	2,705	7.66
111C,112A	38.7	"	"	7,581	"	1.35	140.	"	"	5.33	"	1.22	124.6	"	"	5.23
113C,114A	78.3	"	"	15,340	"	2.15	223	"	"	4.19	"	1.97	201.8	"	"	4.19
115C,116A	116.9	"	"	22,900	"	2.82	295	"	"	3.69	"	2.64	271.0	"	"	3.77
117C,118A	158.2	"	"	30,990	"	3.52	366	"	"	3.40	"	3.26	334.3	"	"	3.42
119C,120A	218.4	"	"	42,780	"	4.46	463	"	"	3.12	"	4.17	427.3	"	"	3.18
9c. d_i = 5.024 cm A = 236.4 cm² Ser II (d_o = 9.87 cm)																
,415A	386.2	25.0	1.266	129,500	-	-	-	-	-	-	0.01082	5.06	484	0.468	2,705	2.40
416C,417A	247.3	24.6	1.279	97,140	0.00970	3.25	347	0.538	2,377	2.09	0.01084	4.02	384.7	0.463	2,762	2.57
418C,419A	165.4	24.6	1.277	64,280	0.00945	2.49	273	0.539	2,369	2.49	0.01086	2.94	280.8	0.464	2,752	2.82
420C,421A	81.02	24.7	1.274	31,950	0.00920	1.62	172	0.541	2,365	3.15	0.01088	1.76	167.3	0.465	2,740	3.37
422C, 423A	27.1	25.0	1.266	10,750	0.00830	0.72	84.3	0.545	2,323	4.58	0.01105	0.92	86.0	0.468	2,705	5.14
424C, 425A	15.8	24.6	1.277	6,216	0.00870	0.50	59.7	0.539	2,369	5.63	0.01125	0.64	58.7	0.464	2,752	6.11
9d. d_i = 25.024 cm A = 236.4 cm² Ser. III (d_o = 6.07)																
,410A	319.1	25.3	1.258	127,400	-	-	-	-	-	-	0.00980	4.42	467	0.472	2,665	2.34
407C,408A	240.2	25.8	1.243	97,090	0.00865	2.70	316.4	0.557	2,232	1.89	0.01000	3.38	350	0.479	2,595	2.31
405C, 406A	162.3	25.0	1.266	64,410	0.00875	2.25	266.3	0.545	2,323	2.48	0.01030	2.70	272	0.468	2,705	2.74
401C, 402A	79.4	25.0	1.266	31,510	0.00865	1.68	201.2	0.545	2,323	3.73	0.01095	1.82	172.6	0.468	2,705	3.54
,404A	26.8	25.0	1.266	10,640	-	-	-	-	-	-	0.01148	0.95	85.4	0.468	2,705	5.21

$$R_d = \frac{V d_i}{\nu} \qquad j'_D = \frac{k}{v} (Sc)^{0.644}$$

Table 10. Mass Transfer at Rotating Electrodes. Ferri-Ferrocyanide Couple

Solution No. A-13 (2.011 N NaOH)

Run No.	V cm/sec	T °C	$\nu \times 10^2$ cm²/sec	R_d	Cathodic Reduction of Ferricyanide: $C_{Ferri} \times 10^3$ mol/cc	I_c mA/cm²	$k_c \times 10^5$ cm/sec	$D \times 10^5$ cm²/sec	Sc	$j'_D \times 10^3$	Anodic Oxidation of Ferrocyanide: $C_{Ferro} \times 10^3$ mol/cc	I_a mA/cm²	$k_a \times 10^5$ cm/sec	$D \times 10^5$ cm²/sec	Sc	$j'_D \times 10^3$
10a, d_i = 5,094 cm, A = 236.4 cm² Ser. I (d_o = 13.39 cm)																
[illegible]	322	25	1.276	[illegible]	0.01226	5.88	406.7	0.539	2,367	2.29	0.01222	5.91	500.8	0.464	2,750	2.56
[illegible]	237.5	"	"	[illegible]	0.01206	4.56	392.2	"	"	2.46	0.01264	4.64	360.5	"	"	2.62
[illegible]	157.5	"	"	61,[illegible]	[illegible]	3.38	295.1	"	"	2.80	0.01306	3.43	271.8	"	"	2.84
[illegible]	76.5	"	"	[illegible]	[illegible]	2.04	180.1	"	"	3.53	0.01346	2.13	164.2	"	"	3.53
464C, [illegible]	[illegible]	"	"	[illegible]	[illegible]	0.98	80.5	"	"	5.00	0.01386	1.02	76.5	"	"	4.72
466C, 467A	15.78	"	"	6,220	[illegible]	0.695	65.7	"	"	6.02	0.01405	0.715	52.7	"	"	5.48
- ,469A	6.84	"	"	2,[illegible]	-	-	-	-	-	-	0.01424	0.450	31.6	"	"	7.58
10b, d_i = 5,094 cm A = 236.4 cm² Ser II (d_o = 9.87 cm)																
470C, 471A	412	25	1.276	[illegible]	0.0118	6.58	573	0.539	2,367	2.07	0.0128	7.12	576	0.464	2,750	2.30
472C, 473A	315	"	"	124,000	0.0117	5.25	445	"	"	2.20	0.0131	5.66	448	"	"	2.33
474C, 475A	236	"	"	92,600	0.0116	4.38	391	"	"	2.47	0.0134	4.56	353	"	"	2.46
476C, 477A	156	"	"	62,200	0.0115	3.27	295	"	"	2.79	0.0136	3.46	264	"	"	2.74
478C, 479A	78	"	"	30,700	0.0114	2.01	183	"	"	3.[illegible]	0.0138	2.16	162	"	"	3.41
480C, 481A	26.6	"	"	10,500	0.0113	0.93	86.5	"	"	4.78	0.0140	1.04	77	"	"	4.74
10c, d_i = 5,094 cm, A = 236.4 cm² Ser. III (d_o = 6.07 cm)																
446C, 447A	240.4	25	1.276	94,600	0.01110	4.15	385.6	0.539	2,367	[illegible]	0.01280	4.52	365.6	0.464	2,750	2.49
448C, 449A	161.5	26	1.276	63,600	0.01110	3.44	320.4	0.539	2,367	[illegible]	0.01535	3.81	295.9	0.464	2,750	3.00

$$R_d = \frac{V d_i}{\nu} \qquad j'_D = \frac{k}{V}(Sc)^{0.644}$$

Table 11. Mass Transfer at Rotating Electrodes.- Ferri-Ferrocyanide Couple

Solution No. 13 (1.983 N. NaOH)

Run No.	V	T	$\nu \times 10^2$	Re_d	Cathodic Reduction of Ferricyanide: $C_{ferri} \times 10^3$	I_c	$k_c \times 10^5$	$D \times 10^5$	Sc	$j'_D \times 10^3$	Anodic Oxidation of Ferrocyanide: $C_{ferro} \times 10^3$	I_a	$k_a \times 10^5$	$D \times 10^5$	Sc	$j'_D \times 10^3$
	cm/sec	°C	cm²/sec		mol/cc	mA/cm²	cm/sec	cm²/sec			mol/cc	mA/cm²	cm/sec			
11a. d_1 = 1.273 cm. A = 61.2 cm.² Ser. II (d_0 = 9.87 cm.)																
2300,231A	[illegible]	[illegible]	1.273	11,100	0.0505	15.15	310.9	0.535	2,379	4.18	0.0507	15.15	309.6	0.460	2,767	4.60
2320,233A	[illegible]	[illegible]	[illegible]	8,184	0.0508	12.68	[illegible]	0.540	2,338	4.70	0.0508	12.35	251.9	0.464	2,722	5.05
2340,235A	[illegible]	[illegible]	1.281	[illegible]	[illegible]	10.25	208.2	0.531	2,412	5.25	0.0509	9.85	200.6	0.456	2,809	5.87
2360,237A	[illegible]	24.3	1.290	3,977	[illegible]	7.84	[illegible]	0.526	2,452	6.08	0.0510	7.82	158.8	0.453	2,848	6.61
2380,239A	20.3	25.0	1.273	[illegible]	[illegible]	5.08	[illegible]	0.535	2,379	7.56	0.0511	5.08	102.9	0.460	2,767	8.35
2400,241A	6.8	25.0	1.273	[illegible]	0.0512	2.55	[illegible]	[illegible]	2,379	11.36	0.0512	2.50	50.6	0.460	2,767	12.25
11b. d_1 = 2.46 cm. A = 117.6 cm² Ser. II (d_0 = 9.87 cm.)																
970,98A	[illegible]	22.0	1.35	2,406	0.05060	2.88	59.4	0.500	2,700	7.33	0.05040	2.71	55.75	0.430	3,140	7.61
990,100A	[illegible]	[illegible]	1.32	7,385	0.05071	6.50	133	0.511	2,583	5.34	0.05070	5.95	121.7	0.439	3,007	5.39
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	0.05122	9.55	193	0.525	2,485	3.80	0.05100	9.25	188.0	0.450	2,888	4.06
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	0.05175	13.40	269	0.532	2,444	3.47	0.05130	12.70	256.5	0.458	2,838	3.33
[illegible]	[illegible]	25.4	[illegible]	[illegible]	0.05194	17.15	348	0.540	2,338	3.15	0.05160	16.25	319.4	0.464	2,722	3.22
[illegible]	217.2	25.6	1.255	[illegible]	0.05275	21.65	426	0.545	2,299	2.86	0.05190	20.50	409.2	0.468	2,677	3.08
11c. d_1 = 2.46 cm. A = 117.6 cm.², Ser. III (d_0 = 6.07 cm)																
870,88A	157.9	25.0	1.273	30,760	0.05055	15.07	309	0.555	2,379	2.93	0.05010	14.30	296	0.460	2,767	3.08
890,90A	119.1	23.0	1.322	22,360	0.05110	12.95	265	0.511	2,587	3.49	0.04970	12.10	252	0.439	3,011	3.67
910,92A	73.7	23.0	1.322	14,700	0.05165	9.65	194	0.511	2,587	3.90	0.04920	9.16	193	0.439	3,011	4.26
930,94A	38.9	[illegible]	1.322	[illegible]	[illegible]	6.20	[illegible]	0.511	2,587	4.98	0.04890	6.00	127.2	0.439	3,011	5.69
950,96A	13.2	23.0	1.322	2,460	[illegible]	3.00	59	0.511	2,587	7.05	0.04843	2.86	61.1	0.439	3,011	8.05
11d. d_1 = 5.024 cm., A = 258.4 cm², Ser. II (d_0 = 9.87 cm)																
4500,451A	16.0	24.7	1.280	6,280	0.0506	2.84	[illegible]	0.531	2,411	5.47	0.0504	2.76	56.7	0.457	2,801	5.87
4520,453A	26.8	25.0	1.272	10,590	0.0509	3.96	80.6	0.535	2,378	4.60	0.0501	3.80	78.6	0.460	2,765	4.82
4540,455A	47.4	25.0	1.272	18,720	0.0512	5.86	114.5	0.535	2,378	3.62	0.0498	5.50	114.5	0.460	2,765	3.98
4560,457A	79.4	25.0	1.272	31,360	0.0515	8.20	165.0	0.535	2,378	3.29	0.0496	8.10	169.5	0.460	2,765	3.51
4580,459A	159.9	25.0	1.272	63,160	0.0518	13.80	270	0.535	2,378	2.62	0.0492	13.70	288.6	0.460	2,765	2.96
4600,461A	241.2	25.0	1.272	95,270	0.0521	17.90	356	0.535	2,378	2.21	0.0489	15.85	335.7	0.460	2,765	2.29
4620,463A	317.5	25.0	1.272	125,300	0.0524	22.00	436	0.535	2,378	2.05	0.0487	21.00	446.8	0.460	2,765	2.30

$$Re_d = \frac{V d_1}{\nu} \quad ; \quad j'_D = \frac{k}{V}(Sc)^{0.644}$$

Table 12. Mass Transfer at Rotating Electrodes, Ferri-Ferrocyanide Couple

Solution No 10, (2.007 N. NaOH)

Run No.	V	T	$\nu \times 10^2$	R_d	Cathodic Reduction of Ferricyanide						Anodic Oxidation of Ferrocyanide					
					$C_{ferri} \times 10^3$	I_c	$k_c \times 10^5$	$D \times 10^5$	Sc	$j'_D \times 10^3$	$C_{ferro} \times 10^3$	I_a	$k_a \times 10^5$	$D \times 10^5$	Sc	$j'_D \times 10^3$
	cm/sec	°C	cm^2/sec		mol/cc	mA/cm^2	cm/sec	cm^2/sec			mol/cc	mA/cm^2	cm/sec	cm^2/sec		
					12a. d_i = 1.873 cm, A = 61.2 cm^2, Ser. II (d_o = 9.87 cm)											
201C,202A	104.6	27.8	1.280	10,870	0.0995	30.2	314.6	0.535	2,355	4.47	0.1010	28.8	295	0.460	2,739	4.61
203C,204A	81.6	27.2	1.277	8,134	"	23.7	247.2	0.526	2,428	4.58	"	22.6	232	0.453	2,819	4.73
205C,206A	60.5	24.4	1.356	6,680	"	18.45	192.2	0.491	2,752	5.23	"	17.66	181	0.422	3,213	5.42
207C,208A	41.1	24.6	1.348	3,891	"	14.90	155.6	0.494	2,729	6.10	"	14.20	146	0.425	3,172	6.39
209C,210A	19.3	25.3	1.328	1,880	"	9.65	100.5	0.503	2,640	8.38	"	9.20	94.4	0.432	3,074	8.82
211C,212A	7.46	25.4	1.326	716	"	5.30	55.2	0.504	2,631	11.80	"	5.00	51.3	0.433	3,062	12.10
213C,214A	4.20	25.3	1.328	403	"	3.32	34.6	0.503	2,640	13.17	"	3.07	31.5	0.432	3,074	13.22
215C,216A	2.00	25.3	1.328	192	"	2.22	23.1	0.503	2,640	18.46	"	1.99	20.4	0.432	3,074	17.98
217C,218A	1.17	25.3	1.328	112	"	1.52	15.9	0.503	2,640	21.72	"	1.37	14.1	0.432	3,074	21.2
					12b. d_i = 2.48 cm, A = 117.6 cm^2, Ser. II (d_o = 9.87 cm)											
58C,59A	12.6	22.8	1.40	2,232	0.0994	5.35	56.7	0.474	2,953	7.59	0.1008	8.04	51.79	0.407	3,440	7.79
60C,61A	40.3	24.2	1.36	7,349	0.0988	12.10	127	0.489	2,781	5.80	0.1014	11.55	118.0	0.421	3,230	5.33
62C,63A	84.4	27.2	1.28	16,360	0.0982	22.28	235	0.527	2,489	4.20	0.1020	20.90	204.9	0.483	2,826	4.06
64C,65A	132.4	26.8	1.29	25,450	0.0976	29.1	309	0.519	2,496	3.58	0.1026	27.1	273.7	0.448	2,892	3.51
66C,67A	163.3	26.2	1.30	31,150	0.0970	33.6	359	0.514	2,529	3.42	0.1032	31.4	315.3	0.442	2,941	3.31
68C,69A	205.6	27.5	1.27	40,180	0.0964	41.55	451	0.528	2,405	3.16	0.1038	37.8	377.4	0.454	2,797	3.05

$$R_d = \frac{V d_i}{\nu} \quad ; \quad j'_D = \frac{k}{V} (Sc)^{0.644}$$

Table 13. Mass Transfer at Rotating Electrodes, Ferri-Ferrocyanide Couple.

Solution No. 9. (2.004 N NaOH)

Run No.	V cm/sec	T °C	$\nu \times 10^2$ cm²/sec	R_d	Cathodic Reduction of Ferricyanide: $C_{ferri} \times 10^3$ mol/cc	I_c mA/cm²	$k_c \times 10^5$ cm/sec	$D \times 10^5$ cm²/sec	Sc	$j'_D \times 10^3$	Anodic Oxidation of Ferrocyanide: $C_{ferro} \times 10^3$ mol/cc	I_a mA/cm²	$k_a \times 10^5$ cm/sec	$D \times 10^5$ cm²/sec	Sc	$j'_D \times 10^3$
13a. d_i = 1.273 cm., A = 61.2 cm², Ser. II (d_o = 9.87 cm)																
- ,276A	114.9	25	1.423	10,280	-	-	-	-	-	-	0.2030	52.0	265.5	0.390	3,649	4.55
2770,278A	81.5	"	"	7,291	0.1988	42.2	219.8	0.484	3,134	4.82	0.2029	42.0	214.4	"	"	5.18
2800,281A	40.4	"	"	3,614	0.1982	28.2	147.8	"	"	6.51	0.2028	26.0	132.6	"	"	6.46
2840,285A	20.0	"	"	1,789	0.1976	16.6	87.0	"	"	7.76	0.2027	16.4	83.9	"	"	8.27
2860,287A	5.8	"	"	808	0.1971	8.8	46.2	"	"	12.1	0.2026	8.9	45.4	"	"	13.1
2900,291A	2.07	"	"	186	0.1961	3.75	19.9	"	"	17.1	0.2024	3.55	18.2	"	"	17.3
13b. d_i = 2.48 cm., A = 117.6 cm², Ser. II (d_o = 9.87 cm)																
1330, 134A	214.9	25	1.423	37,430	0.1990	72.2	376	0.484	3,134	3.12	0.2027	72.0	368	0.390	3,649	3.37
1350,136A	162.7	"	"	28,280	0.1979	55.8	294	"	"	3.53	0.2026	53.4	273	"	"	3.62
1370,138A	109.5	"	"	19,088	0.1960	46.2	239	"	"	3.89	0.2025	43.7	224	"	"	4.03
1390, 140A	78.2	"	"	13,630	0.1945	36.0	186	"	"	4.25	0.2024	33.9	174	"	"	4.37
1410,142A	39.5	"	"	6,880	0.1935	22.3	119	"	"	5.41	0.2023	21.5	110.1	"	"	5.51
1430,144A	13.1	"	"	2,283	0.1928	10.5	57	"	"	7.76	0.2023	10.1	51.8	"	"	7.77
13c. d_i = 5.024 cm, A = 236.4 cm², Ser. II, (d_o = 9.87 cm)																
4840, 485A	26.4	25	1.423	9,381	0.1992	13.60	74.5	0.484	3,134	5.00	0.2030	13.80	70.4	0.390	3,649	5.22
4860, 487A	79.7	"	"	[illegible]	[illegible]	27.8	151.3	"	"	3.36	0.2037	27.40	139.4	"	"	3.44
4880, 489A	172.6	"	"	61,[illegible]	[illegible]	58.6	300.3	"	"	3.11	0.2044	55.6	281.9	"	"	3.21
4900, 491A	346.8	"	"	97,130	0.1930	73.3	390.8	"	"	2.84	0.2050	75.0	379.1	"	"	3.03
4920, 493A	[illegible]	"	"	117,500	0.1969	90.4	475.9	"	"	2.55	0.2024	87.0	445.4	"	"	2.64
4940, 495A	[illegible]	26.7	1.406	182,400	0.1963	100.0	575.6	0.481	3,048	2.57	0.2024	113.0	578.6	0.396	3,548	2.63

$$R_d = \frac{V d_i}{\nu} \qquad j'_D = \frac{k}{V}(Sc)^{0.644}$$

Table A

Ranges of Property Values Studied

System	Rotor dia. cm, d_i	Gap to rotor ratio, h/d_i	Peripheral Velocity, cm/sec	Reynolds No. R_d	Schmidt No. S_c
Benzoic Acid into H_2O	1.94 - 5.98	0.350 - 2.97	1.06 - 200.8	239 - 241,000	835 - 975
Benzoic Acid into 3.65 m glycerol-H_2O	2.02 - 4.30	0.610 - 1.99	8.09 - 362.5	786 - 41,700	4,926 - 5,053
Benzoic Acid into 4.44 m glycerol-H_2O	4.20 - 4.31	1.36	11.6 - 354.6	1,636 - 48,800	10,847 -11,491
Oxidation of ferrocyanide	1.27 - 5.02	0.104 - 3.377	1.17 - 426	112 - 162,000	2,595 - 3,649
Reduction of ferricyanide	1.27 - 5.02	0.104 - 3.377	1.17 - 426	112 - 162,000	2,232 - 3,134

Table B

Coordinates of the General Mass Transfer Correlation Curve for Rotating Cylinders (see Fig. 18)

R_d	$j_D' \times 10^6$
200	18.4
500	13.0
1,000	10.2
4,000	6.53
10,000	4.88
30,000	3.54
60,000	2.96
100,000	2.61
200,000	2.24
300,000	2.05

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